PROGRESS REPORT NO. 8

BEARING LUBRICANT ENDURANCE CHARACTERISTICS AT HIGH SPEEDS AND HIGH TEMPERATURES

PERIOD: July 1, 1964 to September 30, 1964

Contributors

C. J. Wachendorfer

Project Leader:

C. J. Wachendorfer

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Submitted to:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LEWIS RESEARCH CENTER

CLEVELAND 35, OHIO

RESEARCH LABORATORY

SKF INDUSTRIES, INC.

ENGINEERING AND RESEARCH CENTER

KING OF PRUSSIA, PA.

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Approvals: [signatures]

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TABLE OF CONTENTS

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INTRODUCTION

This is the eighth quarterly Progress Report of research performed under Contract NASw-492, "A Study of Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures".

In Phase I of the program the limiting load, speed, and temperature characteristics of high-temperature tool-steel bearings lubricated with the most advanced present day high-temperature lubricating fluids in a nitrogen-blanketed system are being evaluated in the SKF Industries' high-speed high-temperature bearing test machine. Phase II of the program which will commence shortly is to be conducted with multiple bearing groups at the selected test conditions to establish the design life and reliability parameters for bearing-lubricant systems at high speeds and temperatures.

SUMMARY

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Four high-temperature lubricants, viz.; two hydrocarbons, Socony XRM 109F and Kendex Bright Stock 0846; an ester base oil, Esso Turbo 35 and a modified five-ring polyphenyl ether, PWA 524 were used to lubricate twenty consumable electrode vacuum melted (CVM) WB49 tool steel 7205 angular contact ball bearings at speeds up to 40,000 rpm, 365 lbs. thrust load and mean temperatures up to 642°F. Several cage designs manufactured from two of the most wear resistant materials, M-1 (Rc 55) steel and S-Monel (Rc 33), were utilized in bearings tested during this report period to aid in optimizing the cages which will be used in Phase II endurance tests.

A materials screening program closely related to the high speed high-temperature bearing program has continued in which potential cage materials are being evaluated for wear resistance when lubricated with candidate high-temperature oils in a modified flat-washer tester. A corrosion resistant stainless steel hardened to Rc 52 or Rc 57 has been tested with Esso FN-3157 at 500°F and Monsanto OS-124 at 700°F as the lubricants. Two of the best wear resistant materials to date, M-1 (Rc 60) steel and S-Monel (Rc 33), were also tested at 700°F using a new experimental fluid, DuPont MLO 64-9.

A review of the progress of the entire research program was made at a meeting with the sponsor and the remainder of the program was redirected.

Author

CONCLUSIONS

1. CVM M-1 steel balls improved the performance of CVM WB49 steel bearings lubricated with Socony XRM 109F compared to the same bearings run with CVM WB49 steel balls, by reducing the number of ball flakings.

2. Increasing the test speed from 20,000 rpm to 40,000 rpm increases the temperature capabilities of the bearings and lubricants, but not to the extent expected on the basis of the theoretical increase in lubricant film thickness in the bearings indicating that thicker films are required for operation without surface distress at higher speed.

3. Based on test results to date, Socony XRM 109F and Esso Turbo 35 are selected as the hydrocarbon and ester-base oil candidates, respectively for Phase II endurance tests. Their respective limiting temperatures in the present test rigs at 35,000-40,000 rpm and 365 lbs. load are 600°F and 500°F. A modified polyphenyl ether tested at the same speed and load, PWA 524*, exhibited a limiting temperature of 500°F similar to the unmodified oil, Monsanto OS-124. PWA 524 oil is selected for Phase II testing since it appears to have an improved resistance to sludging similar to the less convenient metallic-copper inhibited OS-124.

4. M-1 (Rc 60) steel and S-Monel (Rc 33) are the choice cage materials based on the wear resistance results obtained from tests in the high-speed high-temperature bearing test machine and in the modified flat-washer tester. Corrosion resistant stainless steel, 440 CM, did not wear as well as either of these two materials.

5. DuPont MLO 64-9 fluid produced less wear than Monsanto OS-124 (the only lubricant previously found capable of 700°F operation in cage tests) on an M-1 (Rc 60) steel cage specimen in modified flat-washer tests conducted at 700°F, whereas S-Monel (Rc 33) cages wore nine times faster in MLO 64-9 than in OS-124 at 700°F. (The combination of S-Monel (Rc 33) and OS-124 is the most wear resistant to date at 700°F.) On this basis it appears possible and promising to run full-scale bearing tests using tool steel bearings and cages with the DuPont MLO 64-9 lubricant, which should perform successfully at very high temperatures based on the viscosity.

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* This fluid was made available by courtesy of Pratt and Whitney Aircraft Division of United Aircraft Corporation, East Hartford, Connecticut.

DETAILS

1. Redirection of Remaining Effort

In a meeting held on the 12th of August, representatives of the sponsor and of SKF Industries' agreed on a redirection of the remainder of this program. The details of this agreement, constituting the plan for future work, are given in the letter reproduced in the Appendix.

2. Continued Phase I Testing with Polyphenyl Ether, Hydrocarbon and Ester Base Lubricants

Tests during this report period were conducted on bearings consisting of consumable electrode vacuum melted (CVM) WB49 steel rings assembled with inner ring riding cages manufactured from either age hardened (Rc 33) S-Monel (Enclosures 1 and 2) or hardened (Rc 55) M-1 steel (Enclosure 3) and CVM M-1 steel balls at speeds up to 40,000 rpm, temperatures up to 642°F and under 365 lbs. thrust load. (AFBMA computed L_{10} life = 480 x 10^6 revs. or 200 hours at 40,000 rpm)

Summaries of test results and bearing dimensions before testing are given in Enclosures 4 and 5, respectively. The lubricants used in the tests reported herein were; two mineral oils, Socony XRM 109F and Kendex Bright Stock 0846, a high viscosity ester base oil, Esso Turbo 35, and a modified five ring polyphenyl ether, PWA 524. The temperature-viscosity characteristics of these and other candidate lubricants previously considered are shown in Enclosure 6.

In keeping with the findings reported in (1), the bearing temperatures in all the tests (except run #47) were maintained low enough to provide a lubricant viscosity of 1.0 cs., the viscosity below which surface distress due to marginal lubrication was found to arise at 20,000 rpm. Whenever available, the test bearings had an unmounted radial looseness of 40-50 microns which was found in (2) to be the most desirable. The average radial cage play of all bearings tested was between .0020" to .0031".

Test Results

It is recalled that earlier tests (runs #39 and #40 reported in (3)) conducted with Socony Mobil XRM 109F resulted in fatigue failures and surface distressed bearings presumably related to the poor endurance characteristics of the WB49 balls which had flaked in these tests. A repeat test (run #42) was conducted in which CVM M-1 steel balls and S-Monel cages (Enclosure 1) were assembled with WB49 rings. CVM M-1 steel balls have shown good endurance life in many tests and were expected to give a truer indication of lubricant performance. After 90 hours (108 x 10^6 revs.) at 20,000 rpm and mean temperatures up to 532°F (extrapolated oil viscosity = 2.85 cs.) both bearings were removed and found to be in good condition. No ball flaking had occurred. Some fragment denting was noted to have occurred on the load end bearing inner race. The bore wear of both cages was less than 1.1 mils, which is considered very slight (Enclosure 7 and 8).

An ester-base oil, Esso Turbo 35, with higher viscosity than the Mil-L-7808 esters was used to lubricate bearings with WB49 rings assembled with S-Monel cages (Enclosure 1) and CVM M-1 balls in test run #43 at mean temperatures up to 504°F (oil viscosity = 1.34 cs.) and 20,000 rpm. After 25.9 hours (31.1 x 10^6 revs.) the test was terminated. The load end bearing was slightly glazed and fragment dented while the drive end bearing was in good condition. Seven of twelve balls in the former bearing were also fragment dented. The cage bore wear in both bearings was again very slight (less than 0.2 mils) (Enclosure 9 and 10).

In the first attempt to run at speeds greater than 20,000 rpm, the relatively viscous hydrocarbon Kendex Bright Stock 0846, was selected as the lubricant. Test run #44 was conducted at 40,000 rpm and mean temperatures up to 604°F (extrapolated oil viscosity = 1.39 cs). After 7.5 hours (18.0 x 10^6 revs.) the test was stopped. The load end bearing had glazed and smeared. Two of the cage pockets within this bearing were broken and the bore wear of the S-Monel cage (Enclosure 1) was 5.2 mils. Eight balls were glazed and smeared reducing their diameters considerably (Enclosure 11). In the drive end bearing, the rings were in good condition, but two of its balls had flaked. Its cage bore wear was 0.1 mils (Enclosure 12).

Difficulties encountered in passing through critical shaft speeds with the high-speed gear box used in these tests necessitated limiting the speed in test run #45 to 20,000 rpm. Kendex Bright Stock 0846 was used to lubricate the bearings (WB49 rings, M-1 balls) which were assembled with S-Monel cages (Enclosure 1) at mean temperatures up to 603°F (extrapolated oil viscosity = 1.40 cs). The test was terminated after 93.5 hours (108×10^6 revs.). Both bearings were in slightly glazed condition with four of the balls of the load end bearing either flaked or fragment dented. The cage bore wear in both bearings was minimal (0.0 and 0.3 mils). (Enclosures 13 and 14.)

Black oxide coated WB49 inner and outer races assembled with S-Monel cages (Enclosure 1) and CVM M-1 steel balls were run with Socony XRM 109F as the lubricant in test run #46. Completion of an improved coupling design and of modifications to the gear box enabled the bearings to be tested at 35,000 rpm and mean temperatures up to 609°F (extrapolated oil viscosity = 2.15 cs). After running for 15.6 hours, the tester was shut down by excessive vibration. The bearings appeared to be in good condition except that some wear had occurred on the cage bores (0.3 and 0.6 mils on the load end bearing and drive end bearing, respectively). Since this was a high-speed test, new cages were installed in the test bearings at that time for continued running. The test lasted a total of 28.5 hours (52.3×10^6 revs.). Examination of the bearings indicated that the drive end bearing was slightly glazed while the load end bearing had glazed and flaked near the groove edge of both races and its balls were either flaked or fragment dented. It was noted during disassembly of the test machine that the filter screens in each oil sump were not fully secured and provided an opening through which wear debris could enter the oil stream to the bearing. This no doubt had a severe effect on the final surface appearance of the bearings. The cage bore wear in the second set of cages was 0.3 and 1.0 mils for the drive and load end bearings, respectively (Enclosure 15 and 16).

A modified five-ring polyphenyl ether, PWA 524, designed to have improved resistance to sludging, which has viscosity characteristics similar to the Monsanto OS-124 five-ring polyphenyl ether previously tested was used in test run #47. The bearings were assembled with bore recessed S-Monel cages (Enclosure 2) and run at 35,000 rpm and mean temperatures up to 640°F (oil viscosity = 0.76 cs). The load end bearing glazed and flaked near the groove edge of both races within 2.4 hours (5.0×10^6 revs.). All its balls had also flaked and four of its cage pockets had cracked. The drive end bearing was slightly glazed and fragment dented. The cage bore wear of the load end bearing was 0.8 mils, that of the drive end bearing was 0.1 mils, respectively. (Enclosures 17 and 18.) A black carbon residue was found on the sump filter screens which was similar to that found after tests with copper inhibited Monsanto OS-124.

In the remaining tests reported herein, viz. runs #48, 49, 50 and 51 hardened (Rc 55) M-1 steel cages (Enclosure 3) with bore recesses were assembled in the test bearings.

A repeat test was conducted with PWA 524 polyphenyl ether in run #48 at a higher speed, 40,000 rpm, and lower mean temperature, 535°F max. (oil viscosity = 1.07 cs.). Within 2.1 hours (3.5 x 10^6 revs.), the test was terminated and both bearings were found to be glazed and flaked. Their balls were fragment dented and their cage bores had worn 3.2 and 2.0 mils in the drive end bearing and the load end bearing, respectively. (Enclosure 19 and 20).

In an effort to extend the temperature capabilities of Socony XRM 109F, test run #49 was conducted at 40,000 rpm (previous tests with Socony XRM 109F were run at speeds no higher than 35,000 rpm). Mean bearing temperatures were up to 642°F (extrapolated oil viscosity = 1.95 cs). As shown in Enclosures 21 and 22, the load end bearing was superficially pitted and the drive end bearing was slightly glazed when the test stopped after 12.3 hours (21.6 x 10^6 revs.). Two sets of cages were used during the test when it was discovered after 6.4 hours that 21.8 mils bore wear was taking place at least on the load end bearing.

In test run #50, the bearings were lubricated with Kendex Bright Stock 0846 and run at 40,000 rpm and mean temperatures up to 606°F (extrapolated oil viscosity = 1.38 cs). The bearings were removed after 7.0 hours (10.9 x 10^6 revs.). The drive end bearing had glazed and all its balls had flaked and smeared. The cage bore wear was 6.4 mils. (Enclosure 23). The load end bearing rings were in good condition, but its balls were fragment dented. A cage bore wear of 1.0 mils had taken place. (Enclosure 24).

Esso Turbo 35 oil was used in run #51 and the bearings were tested at 40,000 rpm and mean temperatures up to 568°F (extrapolated oil viscosity = 1.1 cs). Examination of the bearings after 17.0 hrs. (40.8 x 10^6 revs.) revealed that the load end bearing had glazed and flaked and the drive end bearing was in good condition. The cage bore wear was 4.0 and 0.5 mils. in the load end bearing and the drive end bearing, respectively. (Enclosures 25 and 26).

Discussion of Bearing Test Results

CVM M-1 steel balls used in CVM WB49 steel bearings have shown by the results obtained in test run #42 to improve the performance of these bearings with Socony XRM 109F lubricant over that obtained when WB49 steel balls were used (runs #39 and #40 in (3)). Some improvement in the temperature capabilities of Socony XRM 109F has been observed by increasing the test speed from 20,000 rpm (run #42) to above 35,000 rpm (runs #46 and #49). The limiting temperature of this lubricant for glazing-free operation at present appears to be approximately 600°F at 40,000 rpm; whereas, in earlier tests the limiting temperature was 540°F at 20,000 rpm. The other leading hydrocarbon oil candidate, Kendex Bright Stock 0846 also shows some signs of improving its temperature capabilities by increasing the test speed up to 40,000 rpm as evidenced by comparing the results obtained from runs #41 in (3) and #45 with those produced in runs #44 and #50. Based on these results this lubricant's limiting temperature is approximately 580°F at 40,000 rpm, compared to 540°F at 20,000 rpm. Neither lubricant operated at as high temperature at 40,000 rpm as expected on the basis of the increased elastohydrodynamic film thickness due to the increase in speed. (For a 2:1 speed increase, the bearing should operate at the same film condition with half the viscosity, or above 700°F instead of 540°F with either Socony XRM 109F or Kendex Bright Stock 0846.) These results indicate that a greater film thickness is required for glazing-free operation at higher speed, presumably due to the higher rate of heat generation at asperity contacts.

Runs #44 and #50 conducted with Kendex Bright Stock 0846 at 40,000 rpm did not run for as many revolutions as did the 40,000 rpm runs #46 and #49 in which Socony XRM 109F was the lubricant. Also the Socony XRM 109F oil is known to contain additives specially developed for high-temperature use, whereas the Kendex Bright Stock 0846 does not, therefore presumably has better life expectancy in a high-temperature recirculating system.

For these reasons, Socony XRM 109F is selected as the hydrocarbon oil candidate for multiple bearing group endurance tests in Phase II of this program.

In reviewing the most promising ester-base oil candidates, Esso Turbo 35 appears to be the logical choice for Phase II testing, since its limiting temperature as found from runs #43 and #51 is approximately 500°F, (at 20,000 rpm). The nearest rival is Socony RM-139 which permits bearings to operate at 20,000 rpm without surface distress at no higher than 450°F (runs #33 and #36 in (2), and 37 and 38 in (3). It is reasonable to assume that the superiority of Esso Turbo 35 will carry over into higher-speed tests. Its limiting temperatures at 40,000 rpm has not been precisely established, but is between 500°F and 550°F.

As shown in runs #47 and #48, the modified five-ring polyphenyl ether, PWA 524 seemed to exhibit temperature capabilities and coking tendencies similar to copper-inhibited Monsanto OS-124, tested previously (1). Both lubricants seem to have a limiting temperature of approximately 500°F at 40,000 rpm. Since previous cage compatibility tests showed some reduction in the coking tendencies of OS-124 when metallic copper was used as an inhibitor in the system (1,5)* and the present bearing tests show similar coking tendencies for the PWA 524 and the copper-inhibited OS-124, the more convenient form of the inhibitor in PWA 524 makes this oil preferable for Phase II testing.

The evaluation of black oxide coating of the test bearings in one test (run #46) was inconclusive due to inadvertent circulation of wear debris in the oil system. However, the general experience in the SKF Laboratory on the effectiveness of this treatment in reducing lubrication distress in bearings makes it desirable to specify black oxide treatment for the rings of all Phase II test bearings.

It has been observed in tests conducted at speeds greater than 35,000 rpm that only 5 to 10% of the heater capacity in the tester is required to maintain the test bearings at the desired temperature of the order of 600°F. In order to avoid a runaway temperature condition, tests are planned in which the internal clearance between the screw pumps on the test shaft and the pump liner as well as radial cage clearance in the bearings will be increased. Should this remedy the situation, the test machines and bearing cages will be modified accordingly. Otherwise an external means of cooling will be investigated.

* Although not stated specifically in (1) and (5), no metallic copper inhibitor was used for the 700°F test with Monsanto OS-124 in (5), which showed extensive coking and cage specimen wear, whereas copper plates in the oil were used in all subsequent tests at 700°F with OS-124 to act as an inhibitor, and a repeat test in (1), under the same conditions with the same cage specimen material showed less coking and wear than in (5).

Operation of the bearing test machine at speeds greater than 20,000 rpm with new high-speed gear boxes has presented a number of problems which must be overcome for continuous reliable operation at these speeds. Many of these problems uncovered on check-out runs were overcome by minor modifications of the new gear box and drive systems. The one difficulty of some importance is that the gear box and drive operate above the test critical shaft speed. Work is in progress to identify these criticals accurately and to select test speeds and start-up accelerations that prevent operation without incurring damage to the drive quill or the gear box. Check-out tests during which vibration measurements were taken indicated criticals at approximately 26,000 rpm, 38,000 rpm, and above 47,000. A redesign of the drive quill and modifications to the gear box shaft has now enabled satisfactory operation between criticals at a speed of approximately 45,000 rpm. It is planned that Phase II endurance tests will be conducted at this speed.

Lubrication of Cage Bore Guide Surfaces

Twenty-four cages manufactured from S-Monel (Rc 33) or M-1 (Rc 55) steel, were tested in twenty bearings during this report period in order to select the most desirable cage material, heat treatment and design for Phase II endurance tests. All of the cages tested were of wide land inner ring riding design and measured between .0020" to .0031" in radial cage play. Of the fourteen cages manufactured from S-Monel (Rc 33), twelve were machined to the dimensions shown in Enclosure 1 and two contained a bore recess as shown in Enclosure 2. No significant difference in wear was observed between the two cage designs and the amount of wear in both was acceptable. Broken cage pockets were experienced in one cage of each design (run #44, bearing #576 and run #47, bearing #565) presumably caused by flaking of the balls in the bearings.

The remaining ten cages were manufactured from M-1 (Rc 55) steel and contained a bore recess as shown in Enclosure 3. Considerably more wear was experienced with these cages than those manufactured from S-Monel (Rc 33) or M-1 (Rc 65) which had been tested earlier (1). Direct comparison of cage performance is difficult because the M-1 (Rc 55) cages ran longer than the S-Monel (Rc 33) cages, and they ran at higher speeds than the M-1 (Rc 65) cages. Rings and balls in the bearings tested with any of the cages discussed showed a wide range of surface damage after test, with the most severe cases found with each type of cage being closely comparable. On this basis, the severity of operating conditions for all these cage varieties could be considered comparable and it may be concluded that wear performance of the M-1 (Rc 55) cages was inferior.

From results obtained thus far, cages manufactured from either M-1 (Rc 57-60) steel or S-Monel (Rc 33) will be utilized in bearings for endurance tests, with preference given to the S-Monel cages, except with special lubricants that are shown to corrosively attack S-Monel (for example, the DuPont MLO 64-9 fluid discussed in the next section.)

3. Flat Washer Cage Material

Using the modified flat washer tester and the cage configuration described in (4) tests have been conducted during this report period on a corrosion resistant stainless steel, 440 CM of two different hardnesses, RC 52 and Rc 57, both lubricated with Esso FN-3157 and Monsanto OS-124 at 500°F and 700°F, respectively. Tests have also been run at 700°F with cage specimens manufactured from the two materials, M-1 (Rc 60) steel and S-Monel (Rc 33) (previously found particularly wear resistant) using a highly viscous lubricant, DuPont MLO 64-9, which is reported to corrosively attack most steels. The selection of this lubricant as a high-temperature candidate was made on the basis of promising results obtained in tests conducted at NASA Lewis Research Center.

Evaluation of the material-lubricant combination in these tests is based on measurements of average wear scar size performed at 1/2 hour intervals during the test. A description of this method is given in (3).

Test Results

Wear scar measurements produced after the initial hald hour of testing and at the termination of each test are tabulated in Enclosure 27. Curves of the wear scar area growth for the 440 CM cage specimens of both hardenesses, Rc 52 and Rc 57, lubricated with Esso FN-3157 and Monsanto OS-124 at 500°F and 700°F respectively are shown in Enclosure 28 and 29, together with results found on other materials which were tested earlier. The performance of the M-1 steel (Rc 60) and the S-Monel (Rc 33) cage specimens when lubricated with DuPont MLO 64-9 at 700°F is given in Enclosure 30 and compared with their performance when lubricated with Monsanto OS-124 polyphenyl ether at the same temperature in Enclosure 29.

Discussion of Cage Material Screening Results

From Enclosures 28 and 29, it appears that the 440 CM (Rc 52) cage specimen wears more when lubricated with Monsanto OS-124 at 700°F than with Esso FN-3157 at 500°F. With Esso FN-3157 as the lubricant, the 440 CM (Rc 52) cage specimen's wear scar area after the first half hour of running and its wear scar growth during subsequent running was less than that produced with the 440 CM (Rc 57) cage specimens using the same lubricant; whereas, the reverse is true when both specimens were lubricated with Monsanto OS-124 at 700°F. It is interesting to note that the wear of the 440 CM (Rc 57) cage specimens was approximately the same whether they were lubricated with Esso FN-3157 at 500°F or Monsanto OS-124 at 700°F. In any event the 440 CM material hardened to either RC 52 or Rc 57 does not wear as well as M-1 (Rc 60) steel or S-Monel (Rc 33) when lubricated with either Esso FN-3157 at 500°F or Monsanto OS-124 at 700°F. Therefore, the 440 CM test bearings for Phase II testing will be fitted with either M-1 or S-Monel cages.

It can be seen from Enclosure 30 that the M-1 (Rc 60) steel is much more wear resistant than the S-Monel (Rc 33) material when both are run in DuPont MLO 64-9 at 700°F. Examination of the cage specimens after test indicated that the S-Monel (Rc 33) cage specimen had dark wear scars; whereas, the scars in the M-1 (Rc 60) cage specimen were clean and exposed bare metal. The superior performance of the first M-1 (Rc 60) steel specimen was open to question since this specimen had a black coating of lubricant residue and/or oxide on all surfaces as a result of an earlier test with another lubricant, and it could be argued that this disposit resisted corrosive attack by the DuPont fluid. Therefore, a second test was run with the MLO 64-9 fluid using a cleaned M-1 (Rc 60) cage specimen. The wear scars obtained in this test were of similar size to those of the first specimen and represent accordingly the true wear resistance of this material lubricant combination. It follows that M-1 is a suitable material to operate with DuPont MLO 64-9 fluid; whereas, S-Monel is not. The M-1 (Rc 60) steel-MLO 64-9 fluid combination produces less cage wear at 700°F than the same steel with OS-124 polyphenyl ether, but <u>more</u> than S-Monel (Rc 33) with OS-124 fluid.

LIST OF REFERENCES

1. Wachendorfer, C. J., "Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures", Progress Report No. 5., NASA Contract NASw-492.

2. Wachendorfer, C. J., "Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures", Progress Report No. 6., NASA Contract NASw-492.

3. Wachendorfer, C. J., "Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures", Progress Report No. 7., NASA Contract NASw-492.

4. Wachendorfer, C. J., "Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures", Progress Report No. 1., NASA Contract NASw-492.

5. Wachendorfer, C. J., "Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures", Progress Report No. 2., NASA Contract NASw-492.

APPENDIX

SKF INDUSTRIES, INC.

SKF MOTION ENGINEERING

ENGINEERING AND RESEARCH CENTER *BALL AND ROLLER BEARINGS*

September 2, 1964

National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland 35, Ohio

Attention: Mr. William J. Anderson

Reference: Redirection of Contract No. NASw-492, "A Basic Study of Bearing-Lubricant Endurance Characteristics at High Speed and Temperatures"

Gentlemen:

As a result of our meeting in Cleveland on August 12 concerning the best ways to conduct the remaining portions of the subject contract, it was agreed to re-direct the program in order to obtain the most useful information in the area of high-temperature lubrication of rolling bearings based on the results of our studies to date. Our progress towards the original objectives and the efforts to which we agreed to devote the remainder of our current program are reviewed as follows:

As originally conceived, according to our Proposal AL62T007 dated April 10, 1962, and our letter of September 14, 1962 confirming certain modifications to this proposal, the subject research program encompassed the following investigations:

1) Phase I screening of candidate lubricants and bearing materials for maximum temperature, load and speed capability, originally anticipated to utilize 30 to 60 bearings.

2) Determination of the start and stop capabilities of high temperature lubricants selected from the results of Phase I testing. It was intended that these tests would receive only a minor effort sufficient to make qualitative judgments regarding the ability of the selected fluids to start under general ambient temperature conditions, utilizing available test rigs such as the Shell 4-ball wear tester.

3) Phase II endurance testing of 30-bearing groups under conditions selected from the results of Phase I testing (at test speeds in excess of 20,000 rpm) to establish reliability and design parameters for high-speed high-temperature bearing operation. It was intended that at least eleven groups of 30 bearings each would be tested in Phase II under the following conditions:

a) M-1 bearings at high temperature with the most promising polyphenyl ether lubricant from Phase I.

b) M-1 bearings at high temperature with the most promising highly refined mineral oil from Phase I.

c) M-1 bearings at high temperature with the most promising ester-base oil from Phase I.

d) M-1 bearings at ambient temperature with a reference mineral oil.

e) M-1 bearings at high temperature with either polyphenyl ether, highly refined mineral oil or ester-base oil (whichever gives the most favorable operating temperature and life performance) at a lower load calculated to give about 3 times the life as above.

f) WB49 bearings at high temperature with either polyphenyl ether, highly refined mineral oil or ester-base lubricant giving the most favorable operating temperature and life.

g) WB49 bearings at ambient temperature with a reference mineral oil.

h) WB49 bearings at high temperature with either polyphenyl ether, high refined mineral oil or ester-base lubricant giving the most favorable operating temperature and life, but at a lower load calculated to give about 3 times the life as above,

i) WADC 65 or equivalent stainless steel bearings at high temperature with either polyphenyl ether, highly refined mineral oil or ester-base lubricant giving the most favorable operating temperature and life.

j) WADC 65 or equivalent stainless steel bearings at ambient temperature with reference mineral oil.

k) WADC 65 or equivalent stainless steel bearings at high temperature with either polyphenyl ether, highly refined mineral oil or ester-base lubricant giving the most favorable operating temperature and life, but at a lower load calculated to give about 3 times the life as above.

To date, we have tested over 100 bearings in Phase I screening of 11 candidate high temperature lubricants. This additional testing over that originally anticipated has been required for the following reasons:

1) A failure mode of high temperature high speed bearings has been established which indicates the importance of sufficient lubricant viscosity at operating temperature and has thus made it desirable to obtain and test candidate lubricants having the highest possible viscosity at high temperature. Special lubricants having higher viscosity than those conforming to specification Mil-L-9236 and those normally referred to as highly refined mineral oils originally intended for Phase I screening have thus been tested.

2) Engineering criteria have been developed for the design of the cages for high temperature high speed tool steel bearings. Several modifications of the cage design have been tested in addition to those originally anticipated for Phase I screening tests.

3) Another result of the failure mode established in these Phase I screening tests have been the increased importance of surface finish and proper bearing clearance in the performance of tool steel bearings at high speeds and temperatures. As a result, a greater variety of bearing design modifications have been tested in Phase I than originally anticipated.

4) The wear resistance of the cage has emerged as a critical factor in high temperature high speed tool steel bearing operation and a comprehensive series of cage compatability tests have been conducted as a part of the Phase I screening program to determine the most promising cage material for the lubricants and test conditions in this study. The cage compatability testing program which was not originally anticipated as a part of this contract has resulted in a clear choice of cage materials for use in Phase II test bearings.

As a result of the above extended Phase I testing conducted to date, lubricants for Phase II testing and Phase II test conditions can now be selected for the remainder of the program. It is estimated that if all remaining funds and time were devoted to Phase II testing, approximately eight 30-bearing groups could be completed. A total of four SKF Industries' high speed high temperature bearing testers are now becoming operational for the performance of this Phase II testing.

It was agreed, however, that several very recent developments in high temperature lubricants and high temperature bearing materials make it more desirable to continue Phase I type testing on one of the machines instead of devoting all four machines to Phase II testing as originally planned. Therefore, the re-directed program for research to be conducted with the remaining time and funds on the subject contract will be as follows:

1) Phase I screening of candidate lubricants and bearing materials will continue on one high temperature high speed bearing tester for investigation of materials such as:

a) DuPont's perfluorinated polymer MLO-64-9 (if cage compatability tests show promising results as mentioned below).

b) Monsanto's improved MCS525

c) Six-ring polyphenyl ether lubricant

d) Sinclair Turbo-S ester-base oil

e) Vacuum melted M-50 tool steel bearings since the maximum operating temperature with the best test lubricants may not be beyond the temperature limitations of this steel.

f) Vacuum melted modified 52100 steel bearings which have almost as good high temperature operating characteristics as M-50 tool steel, but with the possibility of even greater fatigue life based on preliminary test results in the SKF Laboratory.

2) Cage compatability testing will continue with the screening of potentially useful materials such as:

a) DuPont's perfluorinated polymer MLO-64-9 to establish temperature limits of corrosivity toward stainless steel structural materials in the tester.

b) Molybdenum disulphide suspended in a highly refined mineral oil such as Esso's FN-3157 to explore the possibility of improved high temperature lubricating characteristics of such a suspension.

3) Phase II endurance testing of 30 bearing groups will commence on three speed high temperature bearing testers under the following conditions (since WB49 has higher hot hardness than M-1 tool steel and there are preliminary indications of greater high-temperature bearing life with WB49 bearings, it was agreed that the selected high temperature lubricants of the various types would all be tested with WB49 bearings instead of with M-1 bearings as originally planned).

a) WB49 bearings at 600°F with Socony Mobil 109F highly refined mineral oil.

b) WB49 bearings at 500°F with Esso Turbo 35 ester-base oil.

c) WB49 bearings at 600°F with Socony Mobil 109F highly refined mineral oil at a higher load than that used in the previous groups (C/P = 7.8) to establish the load-life relationship at this temperature.

d) M-1 bearings at 600°F with Socony Mobil 109F highly refined mineral oil.

e) 440C (modified) bearings at 600°F with Socony Mobil 109F highly refined mineral oil.

f) If available machine time permits, a group of WB49 bearings will be run at 600°F with a modified Monsanto OS-124 polyphenly ether oil according to a user's proprietary specification.

A sufficient number of bearings have been manufactured (or are in the process of manufacture) of M-1, WB49 and 440C (modified) to test additional groups of statistically similar bearings after expiration of the current contract (September, 1965). A proposal for such an extension of the subject contract including any low temperature start and stop testing of candidate oils, as required, will be submitted in the next few weeks.

If you have any questions regarding the re-direction of the present program, please contact us.

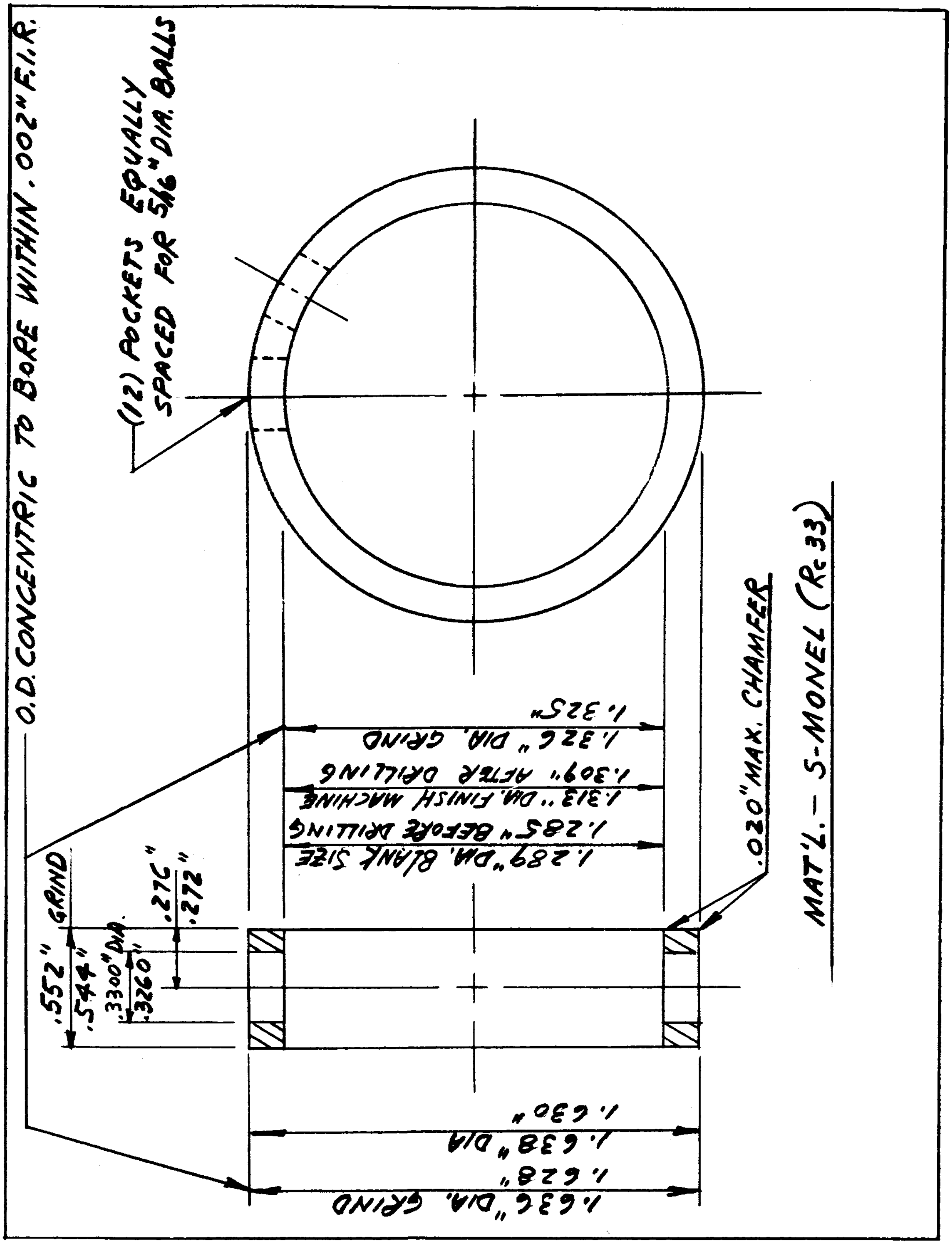
Very truly yours,

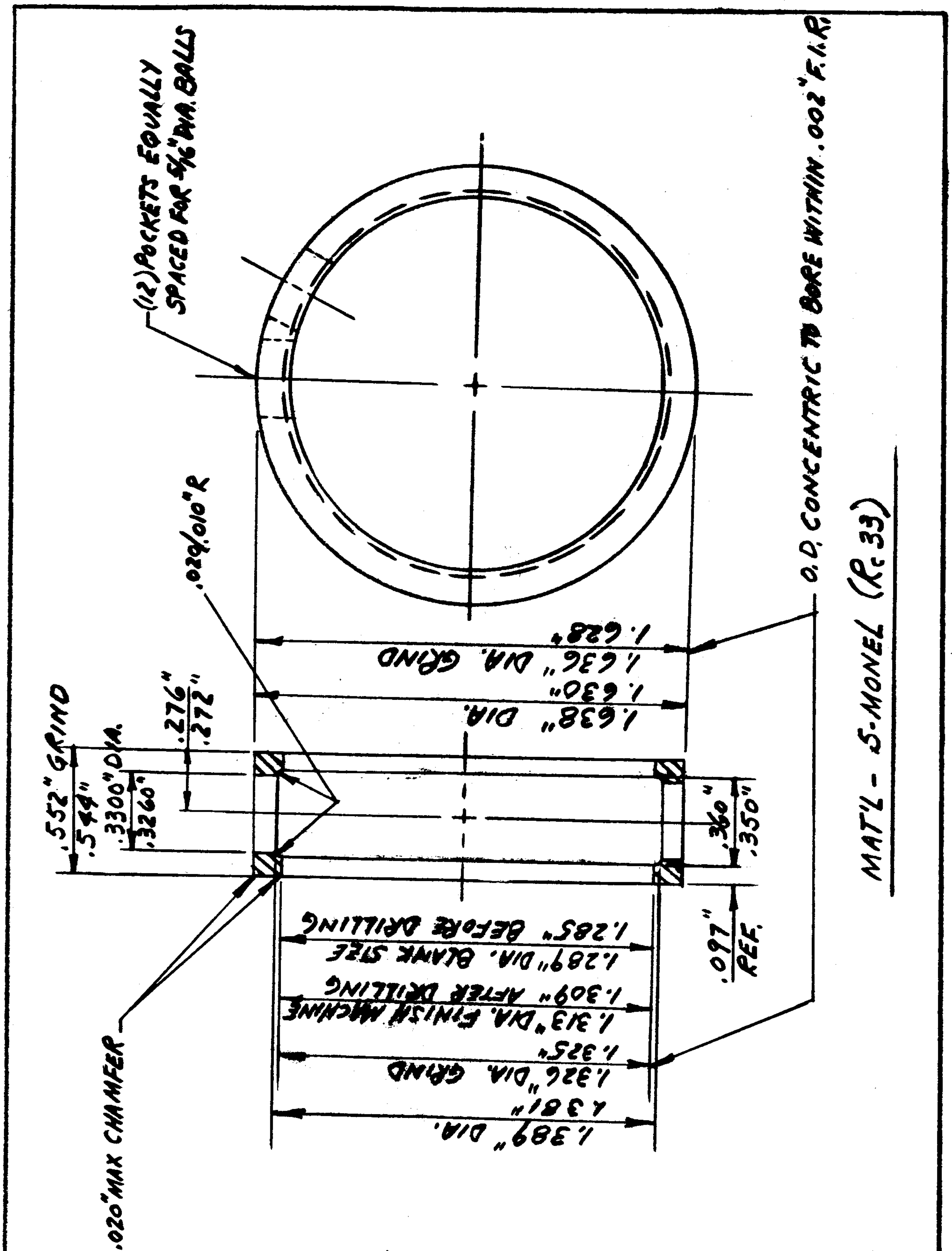
SKF INDUSTRIES, INC.
Engineering & Research Center

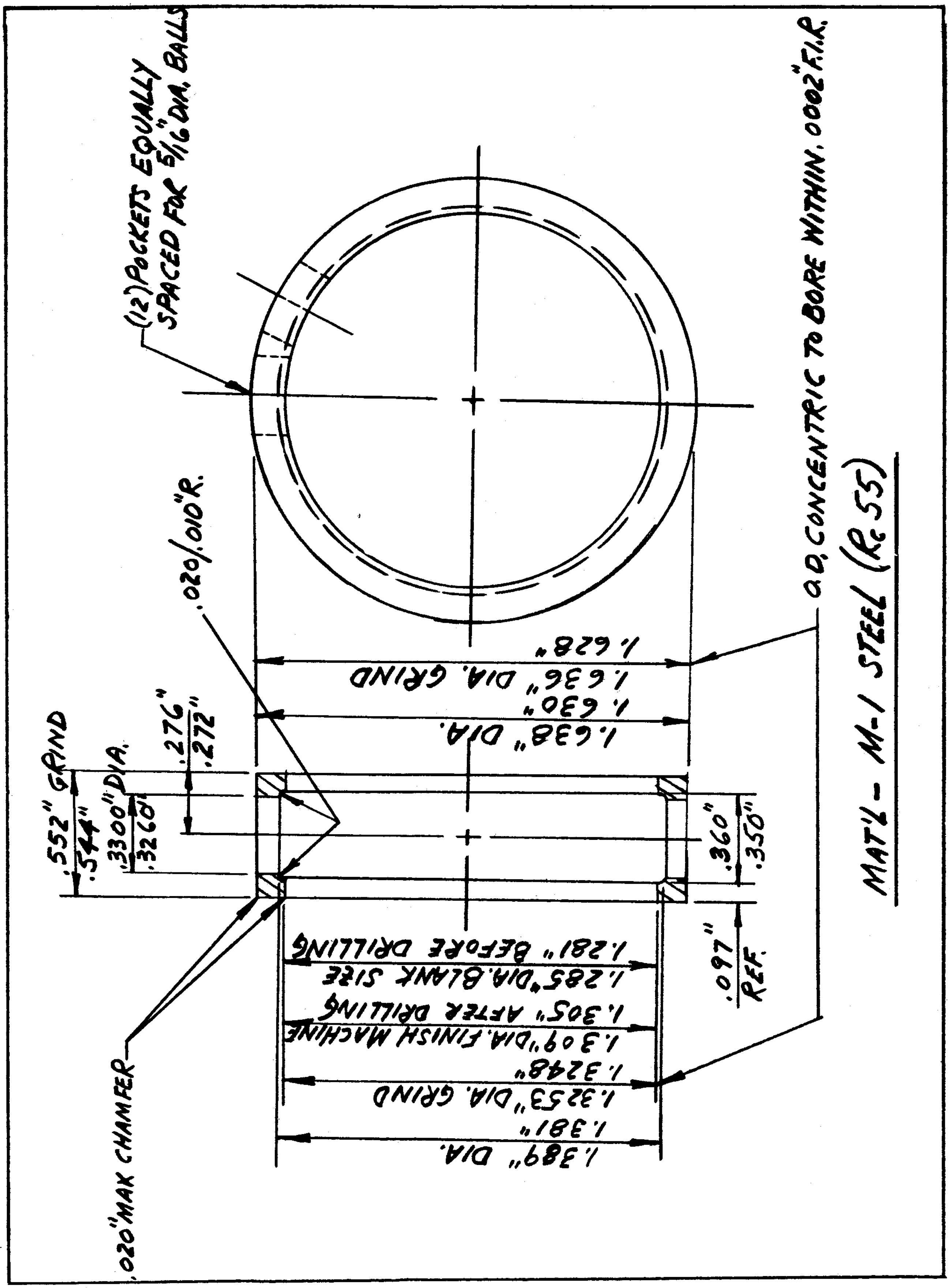
L. B. Sibley

L. B. Sibley, Supervisor
Mechanical Test Section

LBS:kh


O.D. CONCENTRIC TO BORE WITHIN .002" F.I.R.
(12) POCKETS EQUALLY SPACED FOR 5/16" DIA. BALLS
1.325"
1.326" DIA. GRIND
1.309" AFTER DRILLING
1.313" DIA. FINISH MACHINE
1.285" BEFORE DRILLING
1.289" DIA. BLANK SIZE
.020" MAX. CHAMFER
MAT'L. – S-MONEL (Rc 33)
.552" GRIND
.544"
.3300" DIA.
.3260"
.276"
.272"
1.630"
1.638" DIA
1.628"
1.636" DIA. GRIND


(12) POCKETS EQUALLY SPACED FOR 5/16" DIA. BALLS
O.D. CONCENTRIC TO BORE WITHIN .002" F.I.R.
MAT'L - S-MONEL (Rc 33)
.020/.010" R
1.628"
1.636" DIA. GRIND
1.630"
1.638" DIA.
.552" GRIND
.544"
.3300" DIA.
.3260"
.276"
.272"
.360"
.350"
.097"
REF.
1.285" BEFORE DRILLING
1.289" DIA. BLANK SIZE
1.309" AFTER DRILLING
1.313" DIA. FINISH MACHINE
1.325"
1.326" DIA. GRIND
1.381"
1.389" DIA.
.020" MAX CHAMFER


(12) POCKETS EQUALLY SPACED FOR 5/16" DIA. BALLS
O.D. CONCENTRIC TO BORE WITHIN .0002" F.I.R.
MAT'L- M-1 STEEL (R_c 55)
.020/.010"R.
1.628"
1.636" DIA. GRIND
1.630"
1.638" DIA.
.276"
.272"
.552" GRIND
.544"
.3300" DIA.
.3260
.360"
.350"
.097"
REF.
1.281" BEFORE DRILLING
1.285" DIA. BLANK SIZE
1.305" AFTER DRILLING
1.309" DIA. FINISH MACHINE
1.3248"
1.3253" DIA. GRIND
1.381"
1.389" DIA.
.020" MAX CHAMFER

SUMMARIZED RESULTS OF PHASE I TESTING OF CVM WB49 STEEL BEARINGS (#456684)

Run No.	Test Bearing No.	Test Bearing Location	Initial Radial Looseness (Microns)	Test Duration Hours	Test Duration 10^6 Revs.	JBR.	Speed 10^3 RPM	Thrust Load Lbs.	Mean Temperature, °F Bearing	Mean Temperature, °F Housing	Mean Temperature, °F Oil in Sump	Oil Consumed ML	Oil After Test Visc. at 100°F	Oil After Test Acid No.	Oil After Test Solids MG/100ML	(G) Bearing Condition After Test Cage Bore Wear	(Mils)	Raceway
42 (A)	552	Drive	40	90	108	Socony XRM 109F	20	365	532	540	505	5100	449.8	.06	18.0	Very slight	1.1	IR & OR - Good Balls - Good
	540	Load	42						520	540	510					Very slight	0.6	IR - Good (Some fragment denting) OR - Good Balls - Good
43 (A)	582	Drive	39	25.9	31.1	Esso Turbo 35	20	365	476	501	452	795	37.6	.20	84.0	Very slight	0.2	IR & OR - Good Balls - OK
	542	Load	39						504	501	458					Very slight	0.1	IR & OR - Slightly glazed & fragment dented Balls - 7 Fragment dented
44 (A)	581	Drive	38	7.5	18.0	Kendex Bright Stock 0846	40	365	574	577	575	300	398.5	.06	33.5	Very slight	0.1	IR & OR - Good Balls - 2 Flaked
	576	Load	38						604	577	595					Slight Two Broken Pockets	5.2	IR & OR - Glazed & Sheared Balls - (5) Flaked (3) Sheared
45 (A)	571	Drive	38	93.5	108	Kendex Bright Stock 0846	20	365	594	583	556	5150	614.4	.06	14.0	Not appreciable	0.0	IR & OR - Slight Glazing Balls - OK
	568	Load	38						603	583	550					Very slight	0.3	IR & OR - Slightly glazed Balls - 2 Flaked, 2 Fragment Dented
46 (A) (C) (E)	573	Drive	38	28.5	52.3	Socony XRM 109F	35	365	590	585	618	925	271.3	.06	55.0	Very slight	0.6/0.3	IR - Slightly glazed OR - Good Balls - OK
	572	Load	37						609	585	580					Slight	0.3/1.0	IR & OR - Glazed & Flaked on Groove Edge Balls - 5 Flaked, 7 Fragment Dented
47 (A) (B)	574	Drive	37	2.4	5.0	PWA 524	35	365	610	680	668	150	376.3	.06	309.0	Very slight	0.1	IR - Slightly glazed & Fragment Dented OR - Good Balls - OK
	565	Load	38						640	680	615					Very slight Four Pockets Cracked	0.8	IR & OR - Glazed & Flaked on Groove Edge Balls - 12 Flaked

SUMMARIZED RESULTS OF PHASE I TESTING OF CVM WB49 STEEL BEARINGS (#456684)

Run No.	Test Bearing No.	Test Bearing Location	Initial Radial Looseness (Microns)	Test Duration Hours	Test Duration 10^6 Revs.	Lubr.	Speed 10^3 RPM	Thrust Load Lbs.	Mean Temperature, °F Bearing	Mean Temperature, °F Housing	Mean Temperature, °F Oil in Sump	Oil Consumed ML	Oil After Test Visc. at 100°F	Oil After Test Acid No.	Oil After Test Solids MG/100ML	Bearing Condition After Test Cage Bore Wear	Bearing Condition After Test (Mils)	Bearing Condition After Test Raceway
48 (D)	543	Drive	43	1.2 0.9 1.2 0.9	1.4 2.1 1.4 2.1	PWA 524	10-30 40 10-30 40	365	395 510 350 535	380 488 380 488	415 527 380 455	550	378.2	.06	85.0	Slight	3.2	IR & OR - Glazed & Flaked Balls - 6 Fragment Dented 6 - OK
	541	Load	44													Slight	2.0	IR & OR - Glazed & Flaked Balls - 6 Fragment Dented 6 - OK
49 (D) (F)	556	Drive	44	6.0 6.3 6.0 6.3	6.5 15.1 6.5 15.1	Socony XRM 109F	10-30 40 10-30 40	365	294 614 325 642	315 606 315 606	328 600 328 600	730	331.9	.11	71.0	Slight	1.9/0.7	IR - Slightly Glazed & Fragment Dented OR - Very Slightly Glazed
	545	Load	43													Excessive	21.8/12.7	IR - Superficially Pitted OR - Slightly Glazed Balls - OK
50 (D)	561	Drive	45	4.5 2.5 4.5 2.5	4.9 6.0 4.9 6.0	Kendex Bright Stock 0846	10-20 40 10-20 40	365	330 550 360 606	330 545 330 545	320 538 355 515	350	429.7	.06	19.2	Slight	6.4	IR - Glazed OR - Slightly Glazed Balls - Flaked & Smeared
	558	Load	45													Slight	1.0	IR - Good, some fragment denting OR - Good Balls - Fragment dented
51 (D)	554	Drive	47	17	40.8	Esso Turbo 35	40	365	465	550	540	1400	39.7	.28	72.0	Very slight	0.5	IR & OR - Good Balls - OK
	553	Load	47	17	40.8		40		565	550	525					Slight	4.0	IR - Glazed & Flaked OR - Glazed & Peened on Groove Edge Balls - Flaked & Smeared

(A) Test bearings in this run were assembled with M-1 steel balls and S-Monel (Rc33) cages (Enclosure).

(B) Test bearing in this run were assembled with M-1 Steel balls and bore recessed S-Monel (Rc33) cages (Enclosure).

(C) Ball, inner and outer races of the bearing tested in this run were black oxide coated prior to test.

(D) Test bearings in this run were assembled with relapped M-1 steel balls and hardened (Rc55) M-1 Steel cages (Enclosure).

(E) The cage bore wear shown for these bearings is given first for the initial cages which ran 15.6 hours and then the replacement cages which ran 12.9 hours.

(F) The cage bore wear shown for these bearings is given first for the initial cages which ran 6.4 hours and then the replacement cages which ran 5.9 hours.

(G) A bearing is considered to be in good condition if after testing the finishing marks produced in manufacture of the races are still evident in the ball path. A slightly glazed bearing is one in which these finishing marks are not as outstanding or are partially removed.

The unused oils have the following properties:

Lubricant	Visc. at 100°F, CS	Acid No.	Solids, MG/100ML
Socony XRM 109F	419.0	0.10	15.0
Esso Turbo 35	37.0	0.33	30.6
Kendex B.S. 0846	446.9	0.10	4.4
Pratt & Whitney PWA 524	358.9	0.06	9.4

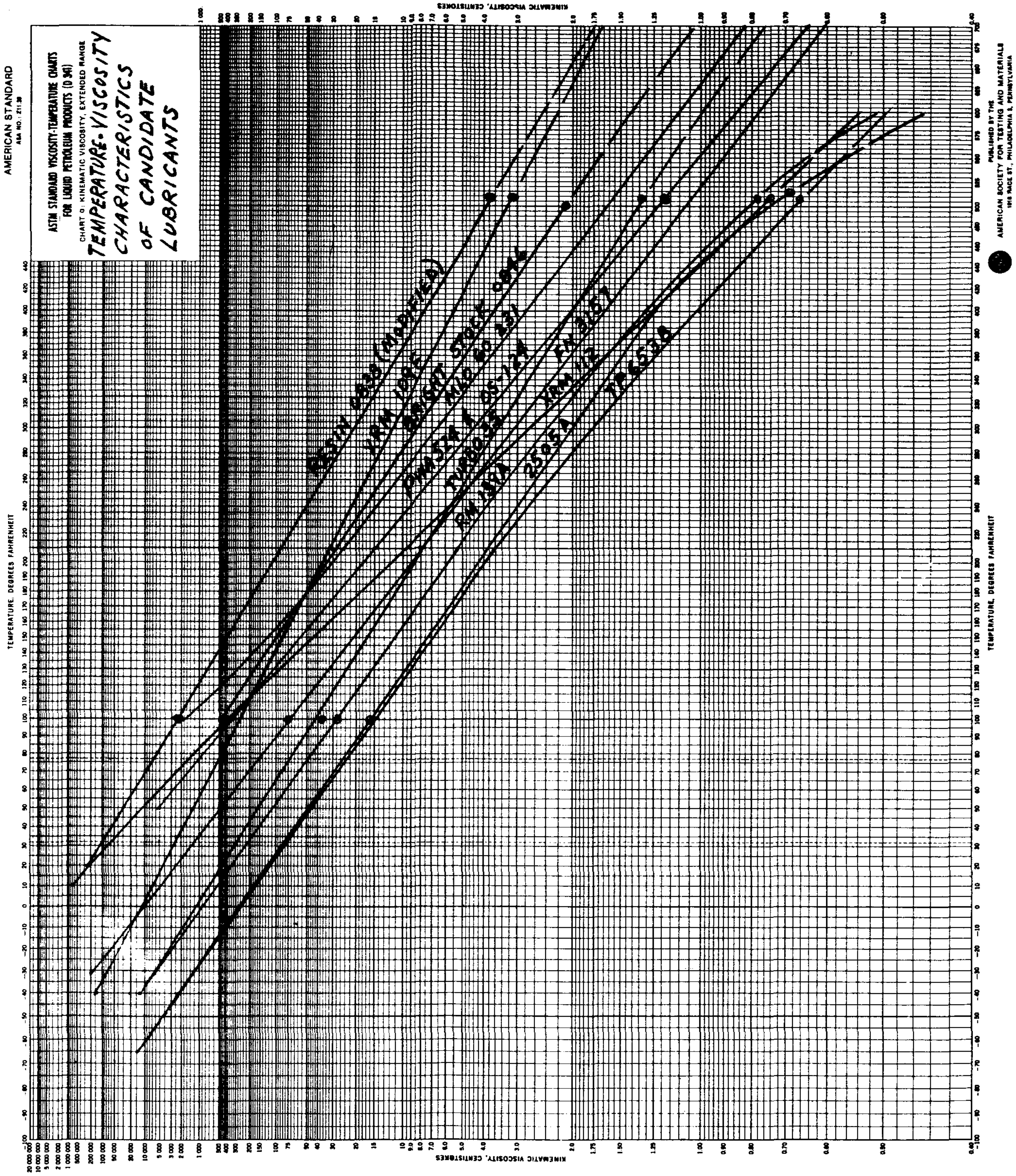
SKF 7205 ANGULAR CONTACT TEST BEARING DIMENSIONS BEFORE TEST

Bearing No.	Average Outside Diameter MM	Average Bore Diameter MM	Contact Angle Degrees	Average Radial Looseness (Microns)	Average Radial Cage Play, Inches	Taper (Microns) OR	Taper (Microns) IR	Out of Roundness (Microns) OR	Out of Roundness (Microns) IR
540	51.999	24.997	18.0	42	.0025	0.0	0.0	1.0	1.0
541	51.996	24.996	19.9	44	.0031	1.5	1.0	2.0	1.0
542	51.997	24.997	19.0	39	.0022	1.0	0.0	2.0	1.0
543	51.999	24.998	19.9	43	.0025	0.0	1.0	2.0	1.0
*545	51.999	24.997	21.3	43	.0022/.0023	0.0	0.0	2.0	2.0
552	51.997	25.001	18.5	40	.002	1.0	1.0	1.0	1.0
553	52.000	24.998	20.8	47	.0028	1.5	2.0	2.0	1.0
554	51.996	24.999	21.8	47	.0029	0.0	0.0	1.0	2.0
*556	52.001	24.997	22.1	44	.0029/.0023	1.5	0.0	3.0	1.0
558	51.999	24.997	23.0	45	.0028	0.0	1.0	1.0	1.0
561	52.000	24.997	23.8	45	.0025	0.5	0.0	2.0	3.0
565	51.997	24.999	19.5	38	.0022	1.0	1.0	1.0	3.0
568	51.999	24.998	19.5	38	.0029	0.5	1.0	3.0	1.0
571	52.000	24.997	19.5	38	.0027	1.0	2.0	1.0	1.0
*572	51.996	24.998	19.5	37	.0024/.0022	1.5	3.0	2.0	1.0
*573	51.995	24.999	19.0	38	.0022/.002	1.0	1.0	1.0	2.0
574	51.999	24.999	19.5	37	.0023	0.0	3.0	1.0	1.0
576	51.997	24.998	19.0	38	.0028	1.0	1.0	1.0	1.0
581	51.997	24.997	19.0	38	.0027	1.0	1.0	1.0	1.0
582	51.996	24.997	19.0	39	.0025	0.0	0.0	2.0	1.0

* The average radial cage play of these bearings is given first for the initial cage used in testing each bearing and then for its replacement cage.

S K F Bearing Tolerances	Maximum	Minimum
Outside Diameter (MM)	52.000	51.990
Bore Diameter (MM)	25.000	24.995
I.R. Taper (Microns)	8.0	-
O.R. Out of Roundness (Microns)	5.0	-
I.R. Out of Roundness (Microns)	5.0	-
	5.0	-
O.R. Groove Conformity (%)	53.3	52.6
I.R. Groove Conformity (%)	52.3	51.6
Radial Looseness	40.0	30.0

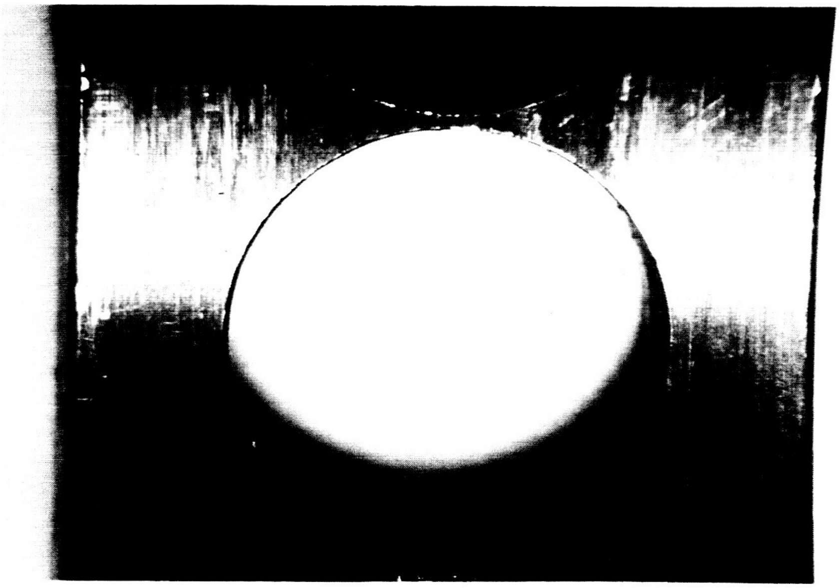
ENCLOSURE 6


AMERICAN STANDARD
ASTM STANDARD VISCOSITY-TEMPERATURE CHARTS FOR LIQUID PETROLEUM PRODUCTS (D 341)
CHART D: KINEMATIC VISCOSITY, EXTENDED RANGE
TEMPERATURE-VISCOSITY CHARACTERISTICS OF CANDIDATE LUBRICANTS
KINEMATIC VISCOSITY, CENTISTOKES
TEMPERATURE, DEGREES FAHRENHEIT
PUBLISHED BY THE AMERICAN SOCIETY FOR TESTING AND MATERIALS
BRIGHT STOCK
OS-124
TURBO 35
XRM 112
2505A

ENCLOSURE 7 AL64T055

UNFAILED WB49 TOOL STEEL BEARING AFTER RUNNING 108 x 10^6 REVOLUTIONS AT 20,000 RPM, A MEAN TEMPERATURE OF 532°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING SOCONY 109-F OIL IN A N_2 BLANKET

(BEARING NO. 552 ON DRIVE END FROM RUN NO. 42)



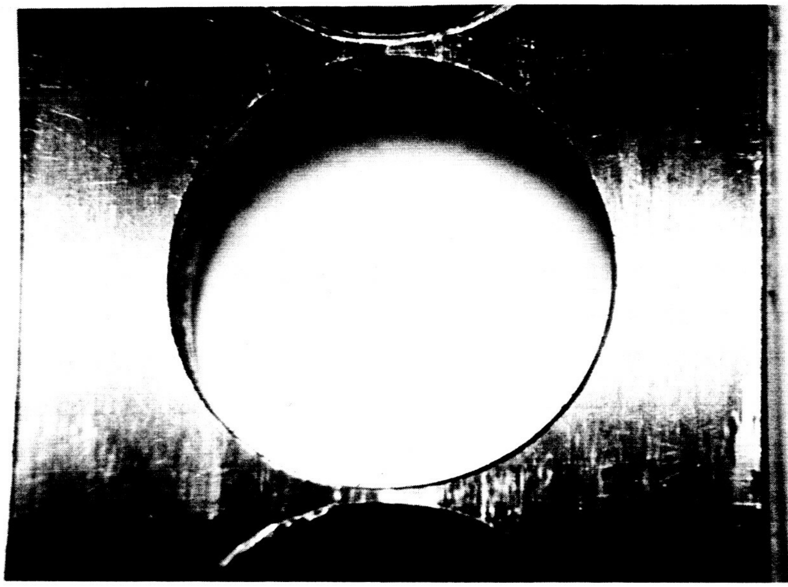
CAGE

INNER RACEWAY

OUTER RACEWAY

UNFAILED WB49 TOOL STEEL BEARING AFTER RUNNING 108 x 10^6 REVOLUTIONS AT 20,000 RPM, A MEAN TEMPERATURE OF 520°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING SOCONY 109-F OIL IN A N_2 BLANKET

(BEARING NO. 540 ON LOAD END FROM RUN NO. 42)



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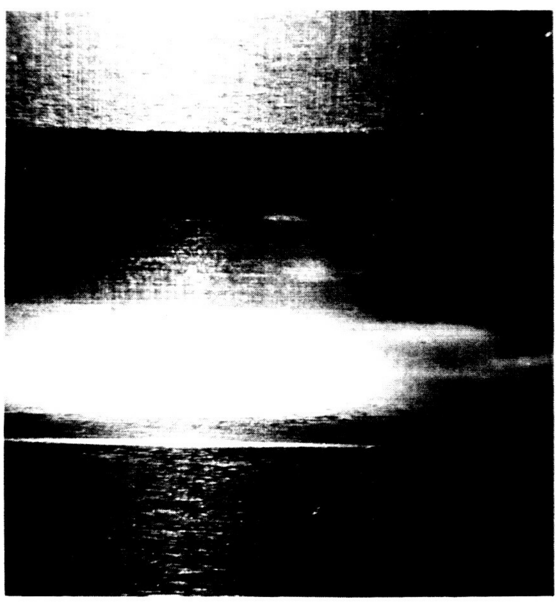

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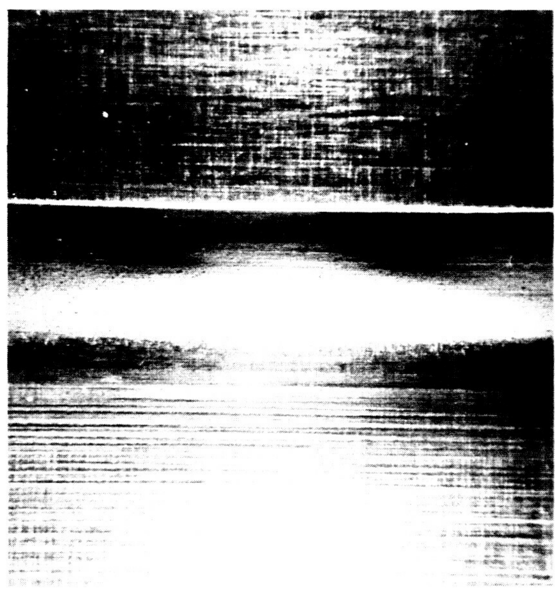
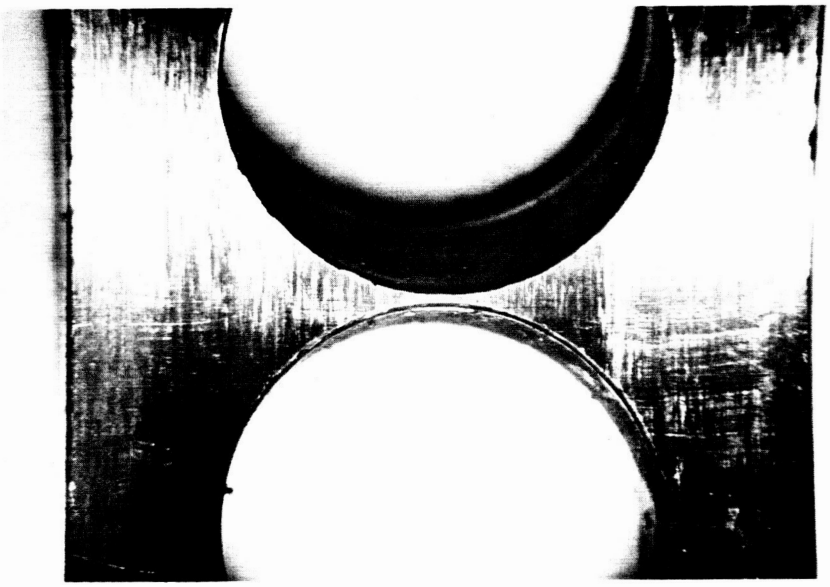


OUTER RACEWAY

ENCLOSURE 9 AL64T055

UNFAILED WB49 TOOL STEEL BEARING AFTER RUNNING 31.1 x 10^6 REVOLUTIONS AT 20,000 RPM, A MEAN TEMPERATURE OF 504°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING ESSO TURBO 35 OIL IN A N_2 BLANKET

(BEARING NO. 542 ON LOAD END FROM RUN NO. 43)



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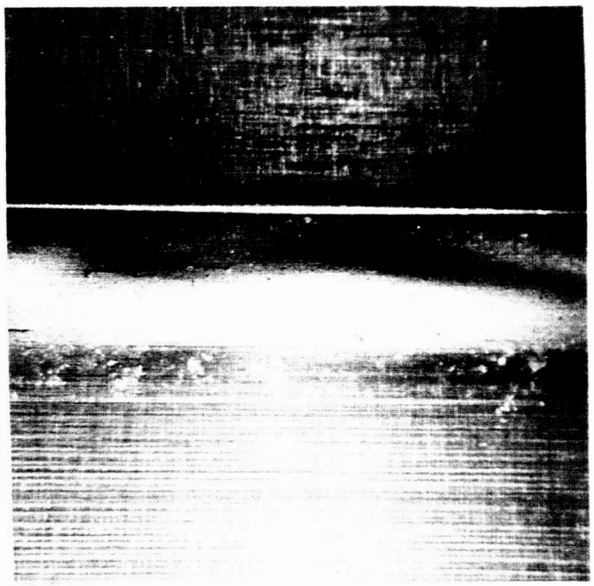
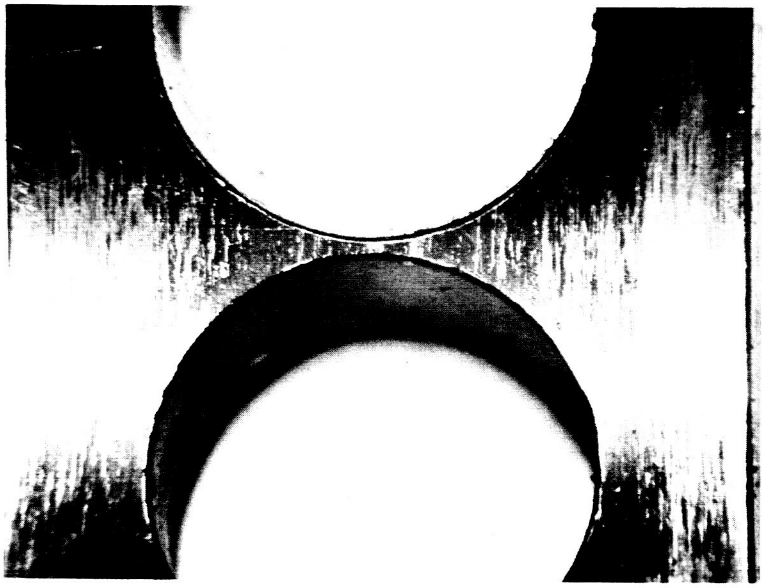
INNER RACEWAY



OUTER RACEWAY

UNFAILED WB49 TOOL STEEL BEARING AFTER RUNNING 31.1 x 10^6 REVOLUTIONS AT 20,000 RPM, A MEAN TEMPERATURE OF 476°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING ESSO TURBO 35 OIL IN A N_2 BLANKET

(BEARING NO. 582 ON DRIVE END FROM RUN NO. 43)



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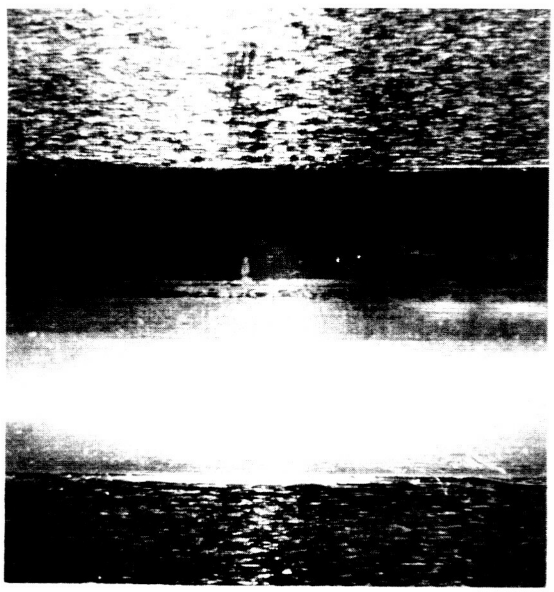
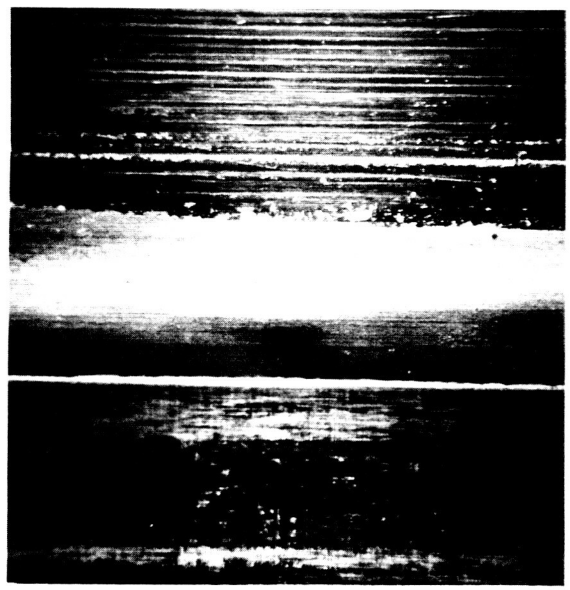


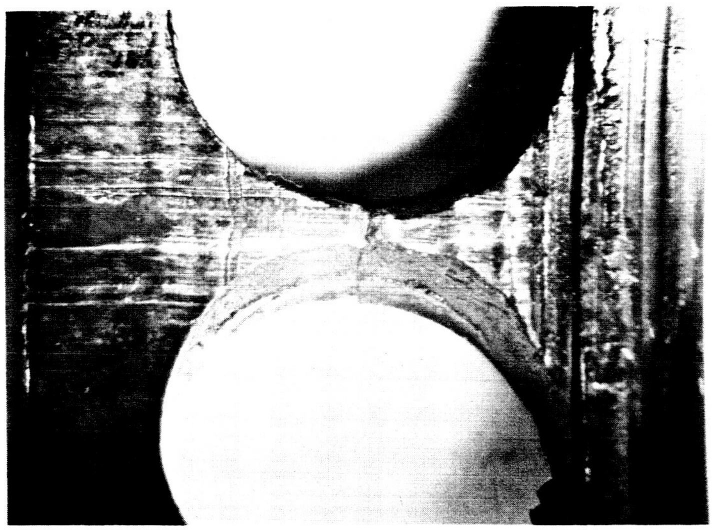
INNER RACEWAY



OUTER RACEWAY

FAILED WB49 TOOL STEEL BEARING AFTER RUNNING 18.0×10^6 REVOLUTIONS AT 40,000 RPM, A MEAN TEMPERATURE OF 604°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING KENDEX 0846 OIL IN A N_2 BLANKET

(BEARING NO. 576 ON LOAD END FROM RUN NO. 44)



CAGE

BALL

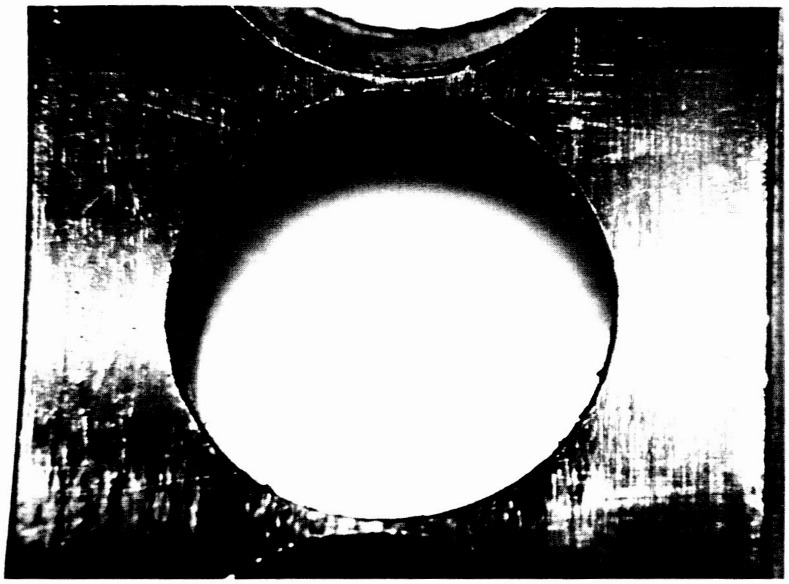
INNER RACEWAY

OUTER RACEWAY

ENCLOSURE 12 AL64T055

FAILED WB49 TOOL STEEL BEARING AFTER RUNNING 18.0 x 10^6 REVOLUTIONS AT 40,000 RPM, A MEAN TEMPERATURE OF 574°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING KENDEX 0846 OIL IN A N_2 BLANKET

(BEARING NO. 581 ON DRIVE END FROM RUN NO. 44)



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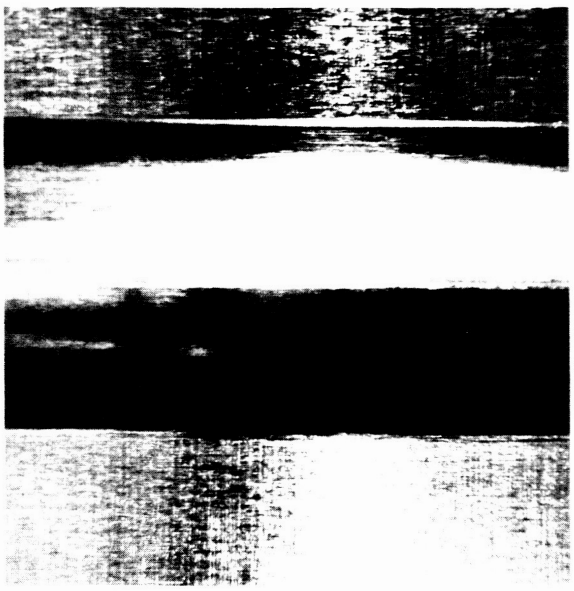
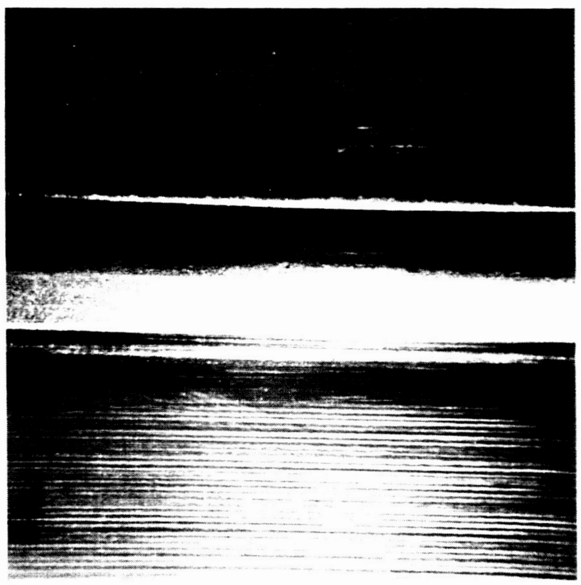


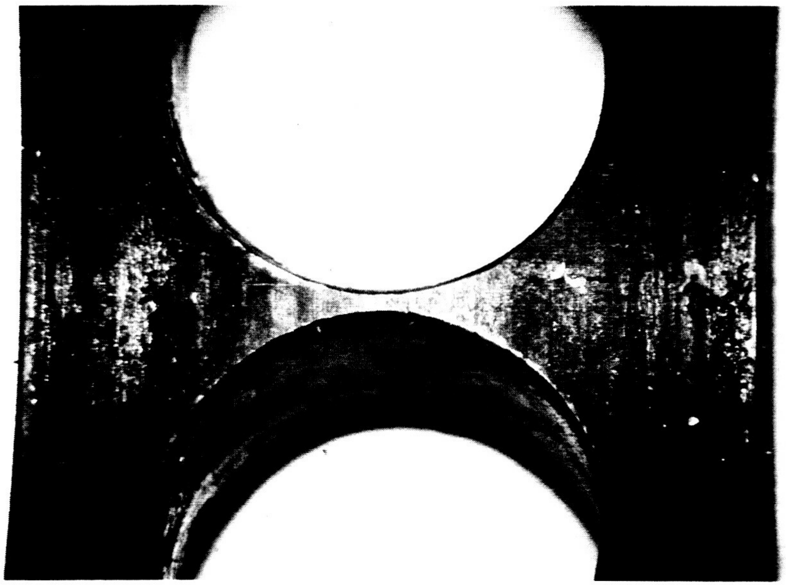
INNER RACEWAY



OUTER RACEWAY

UNFAILED WB49 TOOL STEEL BEARING AFTER RUNNING 108 x 10^6 REVOLUTIONS AT 20,000 RPM, A MEAN TEMPERATURE OF 594°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING KENDEX 0846 OIL IN A N_2 BLANKET

(BEARING NO. 571 ON DRIVE END FROM RUN NO. 45)



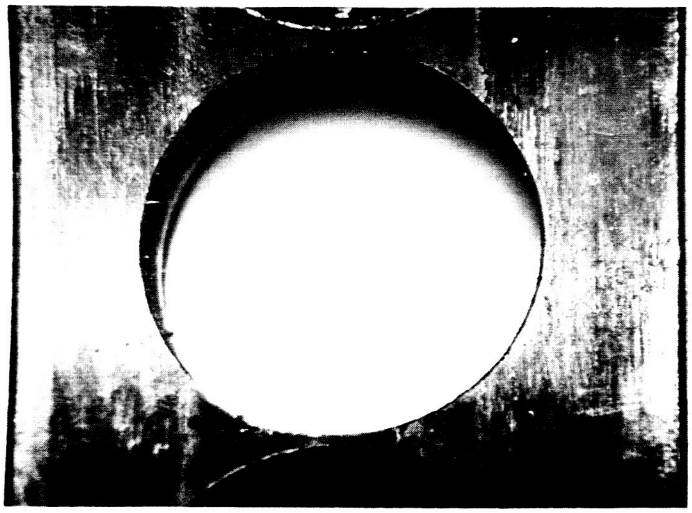
CAGE

INNER RACEWAY

OUTER RACEWAY

FAILED WB49 TOOL STEEL BEARING AFTER RUNNING 108 x 10^6 REVOLUTIONS AT 20,000 RPM, A MEAN TEMPERATURE OF 603°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING KENDEX 0846 OIL IN A N_2 BLANKET

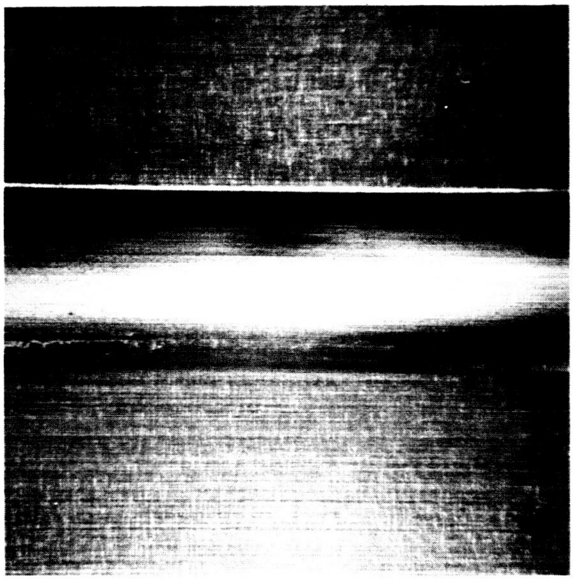
(BEARING NO. 568 ON LOAD END FROM RUN NO. 45)



CAGE

BALL

INNER RACEWAY

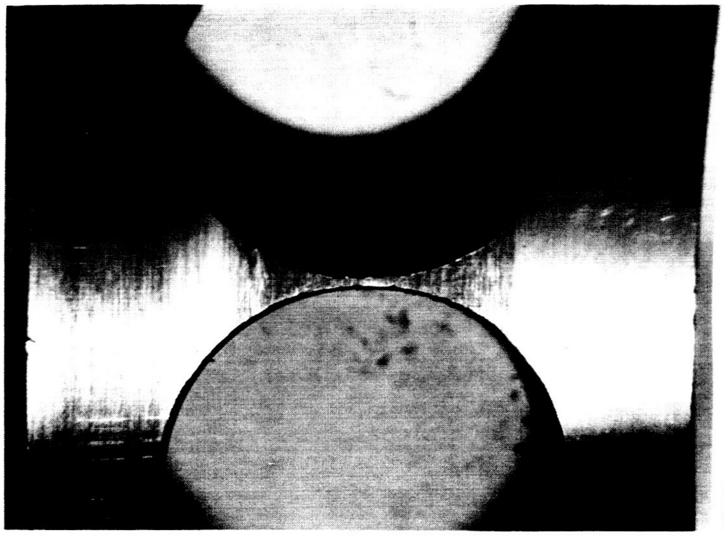


OUTER RACEWAY

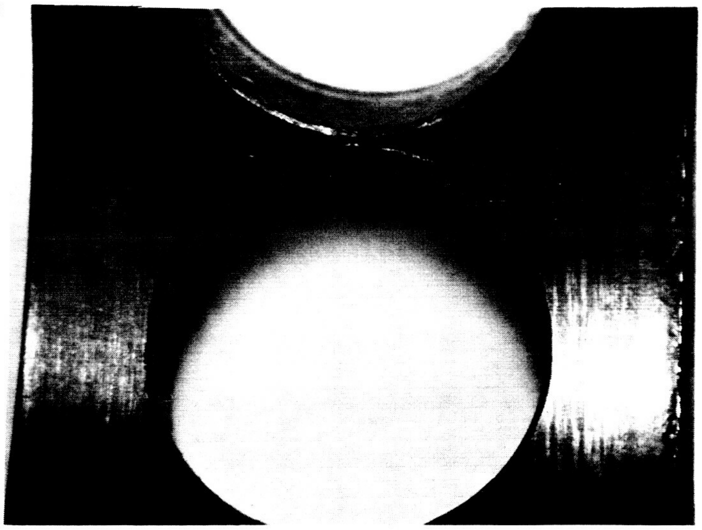
ENCLOSURE 15 **AL64T055**

UNFAILED WB49 TOOL STEEL BEARING AFTER RUNNING 52.3 x 10^6 REVOLUTIONS AT 35,000 RPM, A MEAN TEMPERATURE OF 590°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING SOCONY 109-F OIL IN A N_2 BLANKET

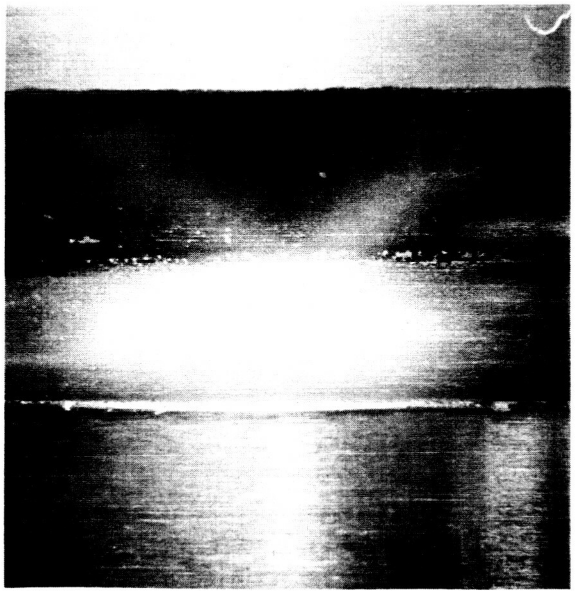
(BEARING NO. 573 ON DRIVE END FROM RUN NO. 46)



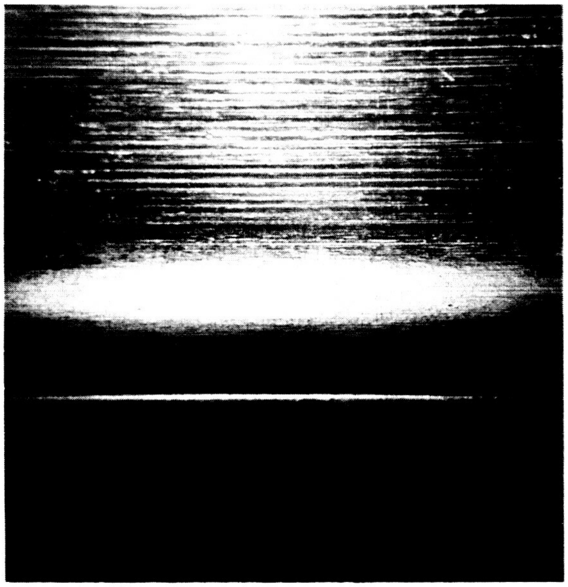
CAGE-1



CAGE



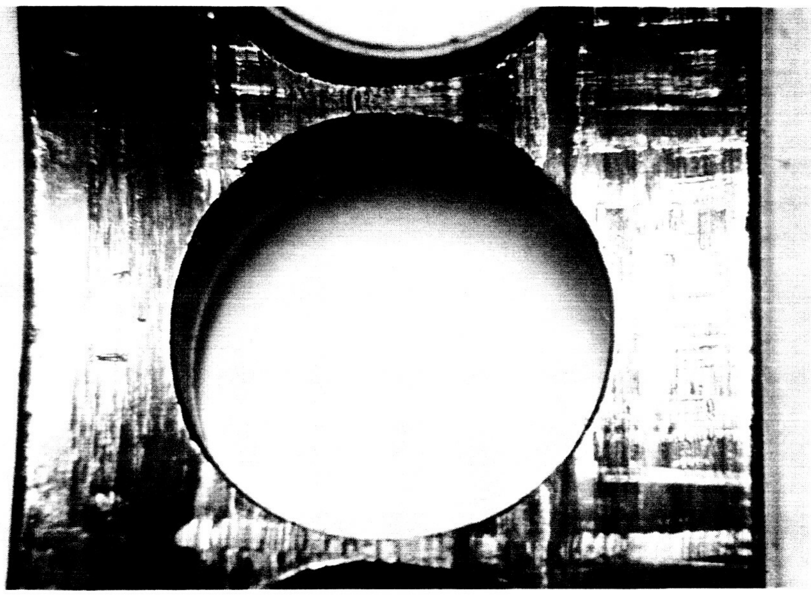
INNER RACEWAY



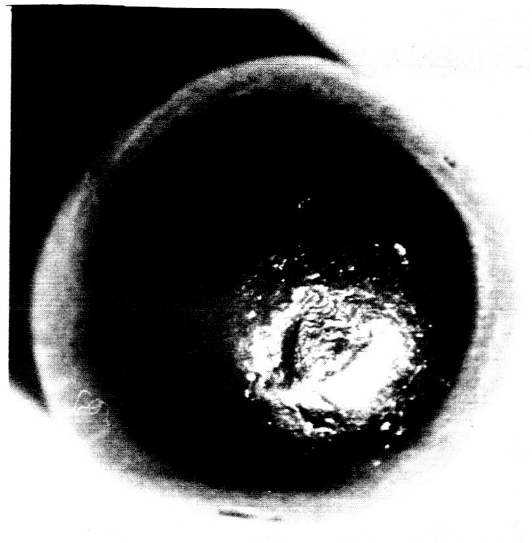
OUTER RACEWAY

FAILED WB49 TOOL STEEL BEARING AFTER RUNNING 52.3 x 10^6 REVOLUTIONS AT 35,000 RPM, A MEAN TEMPERATURE OF 609°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING SOCONY 109-F OIL IN A N_2 BLANKET

(BEARING NO. 572 ON LOAD END FROM RUN NO. 46)

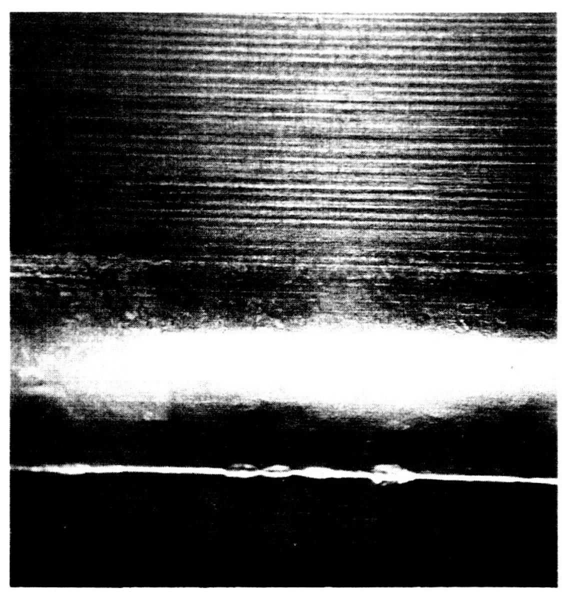


CAGE



BALL

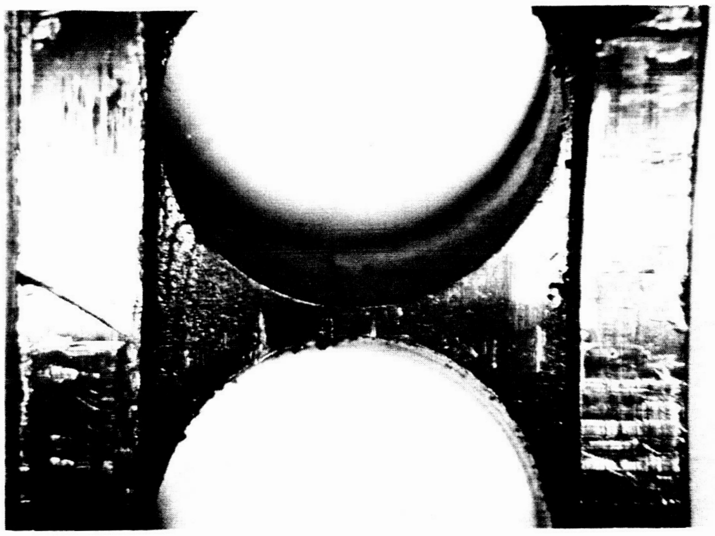
INNER RACEWAY



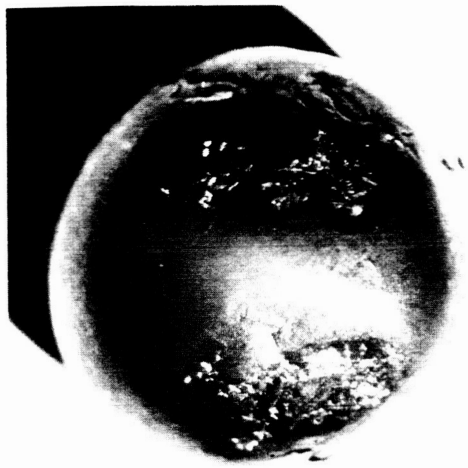
OUTER RACEWAY

FAILED WB49 TOOL STEEL BEARING AFTER RUNNING 5×10^6 REVOLUTIONS AT 35,000 RPM, A MEAN TEMPERATURE OF 640°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING PWA 524 OIL IN A N_2 BLANKET

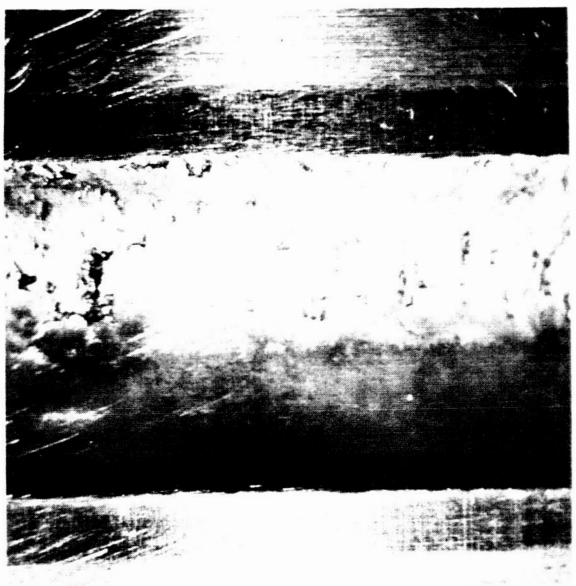
(BEARING NO. 565 ON LOAD END FROM RUN NO. 47)



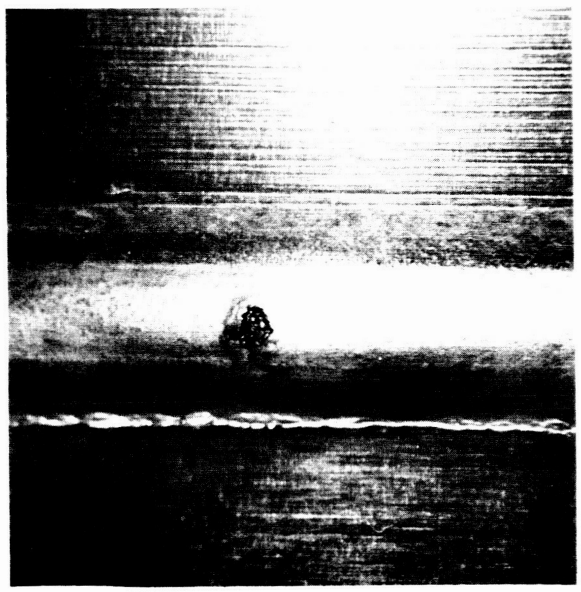
CAGE



BALL



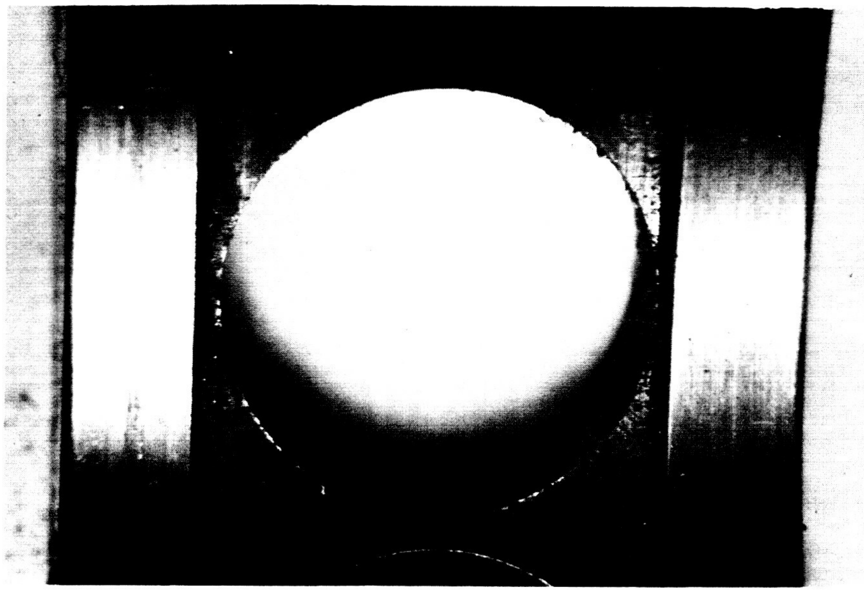
INNER RACEWAY



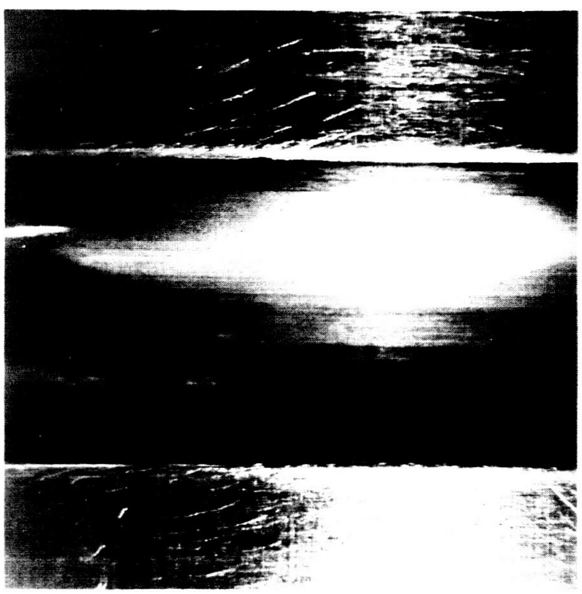
OUTER RACEWAY

UNFAILED WB49 TOOL STEEL BEARING AFTER RUNNING 5 x 10^6 REVOLUTIONS AT 35,000 RPM, A MEAN TEMPERATURE OF 610°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING PWA524 OIL IN A N_2 BLANKET

(BEARING NO. 574 ON DRIVE END FROM RUN NO. 47)



CAGE



INNER RACEWAY

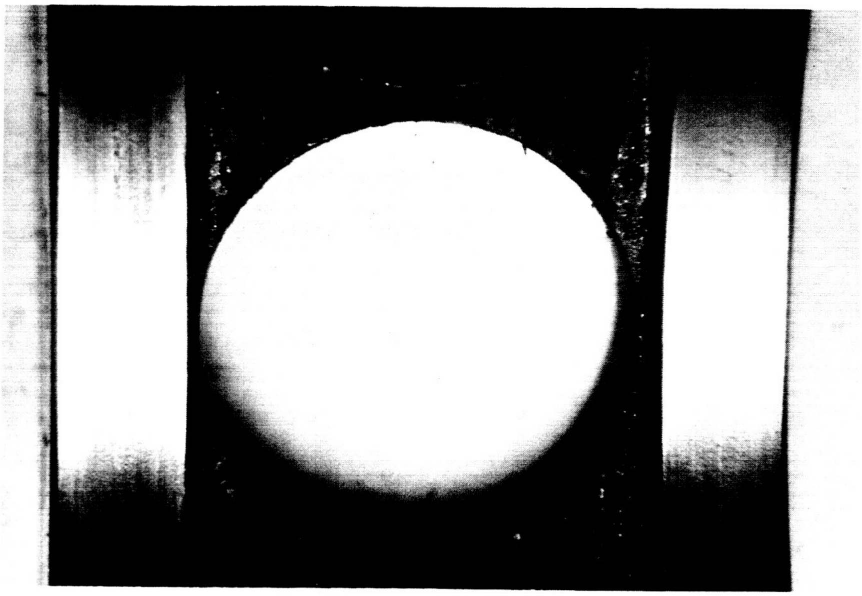
OUTER RACEWAY

ENCLOSURE 19

AL64T055

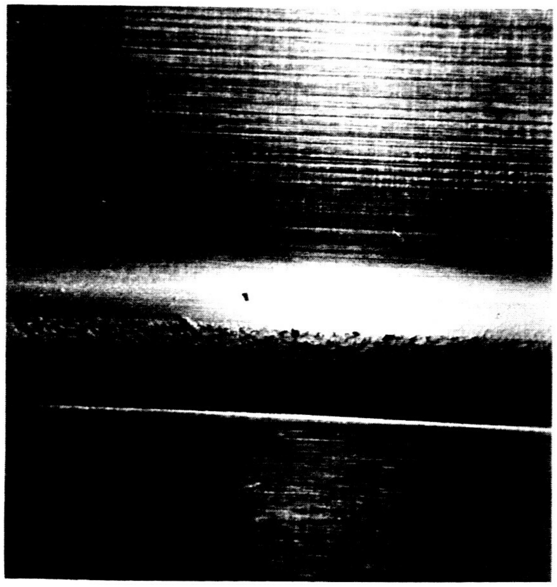
FAILED WB49 TOOL STEEL BEARING AFTER RUNNING 3.5 x 10^6 REVOLUTIONS AT 40,000 RPM, A MEAN TEMPERATURE OF 510°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING PWA 524 OIL IN A N_2 BLANKET

(BEARING NO. 543 ON DRIVE END FROM RUN NO. 48)



CAGE

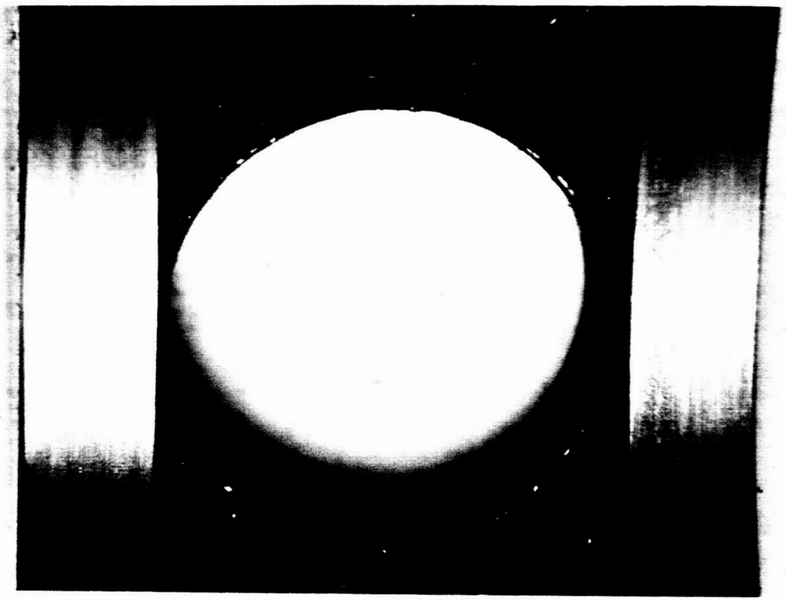
INNER RACEWAY



OUTER RACEWAY

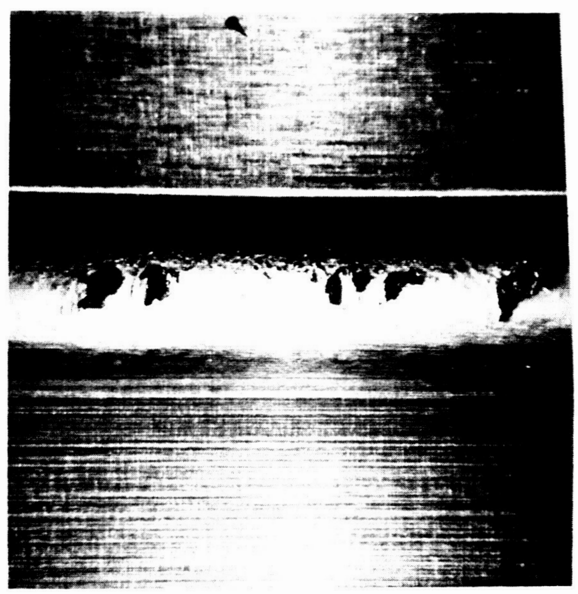
FAILED WB49 TOOL STEEL BEARING AFTER RUNNING 3.5×10^6 REVOLUTIONS AT 40,000RPM, A MEAN TEMPERATURE OF 535°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING PWA 524 OIL IN A N_2 BLANKET

(BEARING NO. 541 ON LOAD END FROM RUN NO. 48)



CAGE

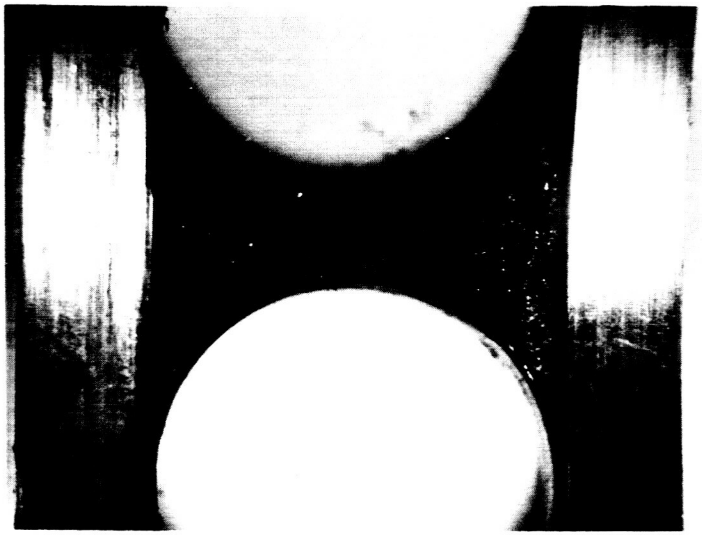
INNER RACEWAY



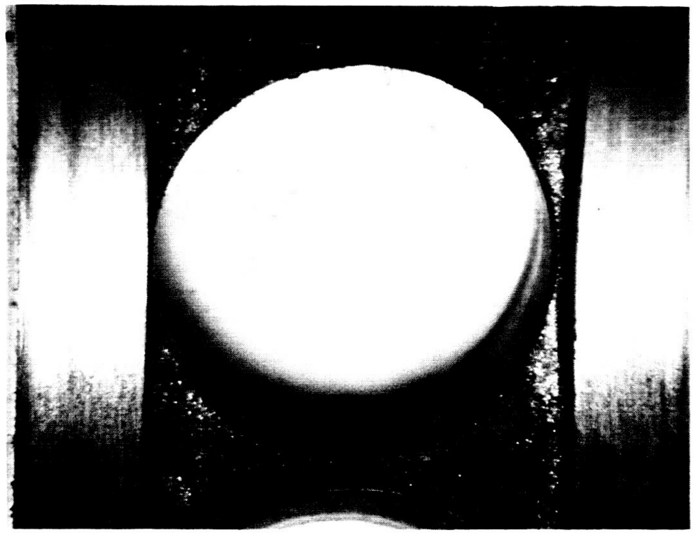
OUTER RACEWAY

UNFAILED AB49 TOOL STEEL BEARING AFTER RUNNING 21.6 x 10^6 REVOLUTIONS AT 40,000 RPM, A MEAN TEMPERATURE OF 642°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING SOCONY 109-F OIL IN A N_2 BLANKET

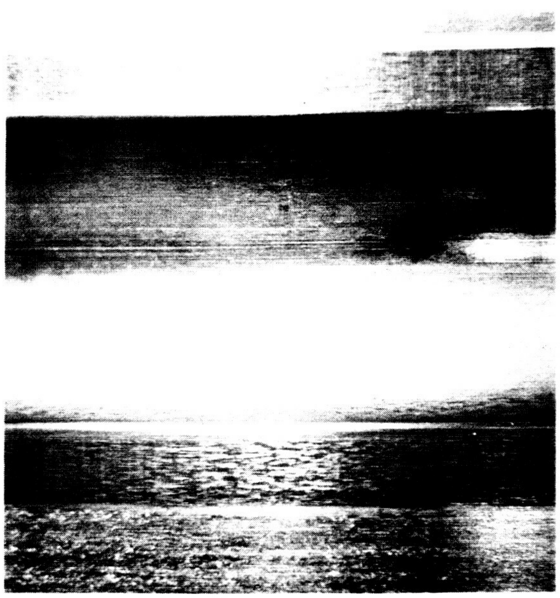
(BEARING NO. 545 ON LOAD END FROM RUN NO. 49)



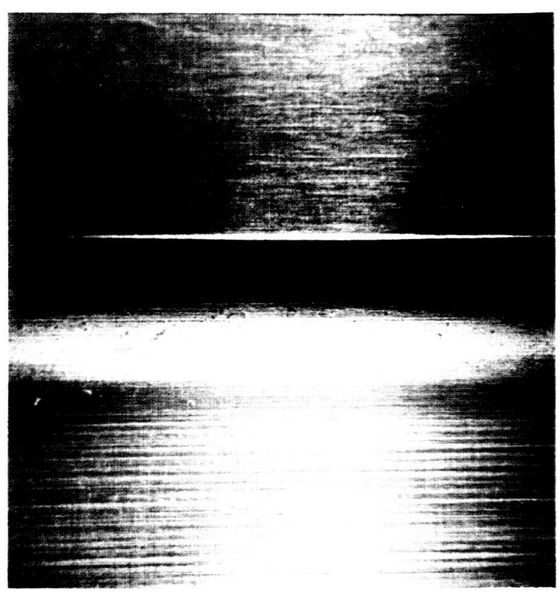
CAGE-1



CAGE



INNER RACEWAY

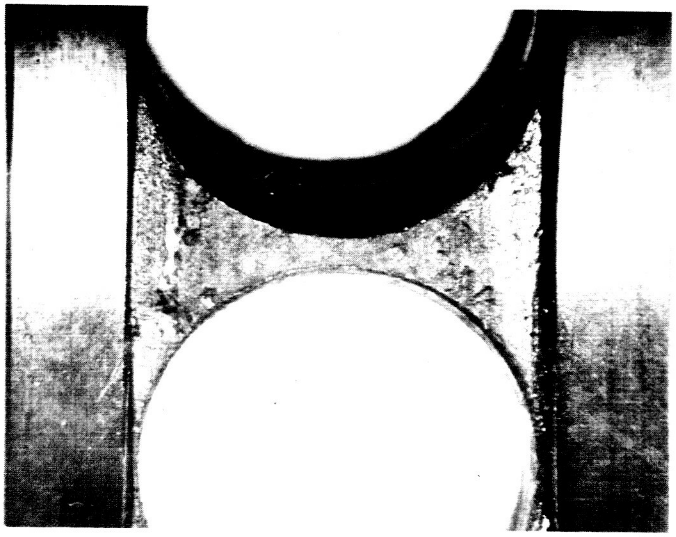


OUTER RACEWAY

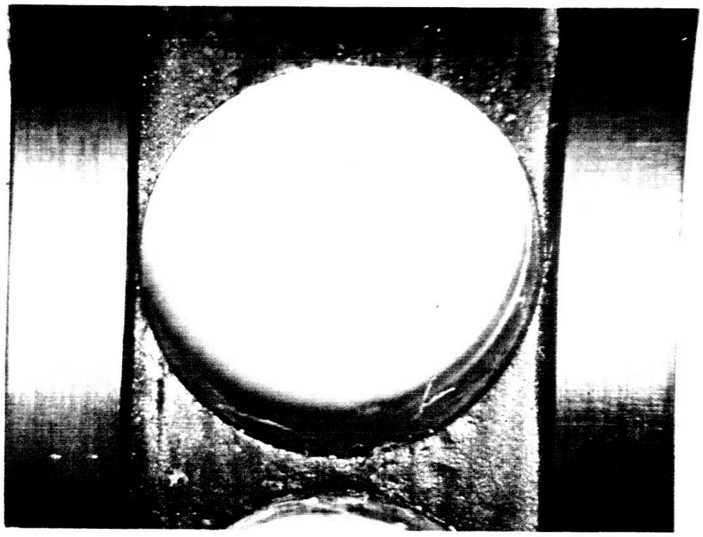
ENCLOSURE 22 AL64T055

UNFAILED WB49 TOOL STEEL BEARING AFTER RUNNING 21.6 x 106 REVOLUTIONS AT 40,000 RPM, A MEAN TEMPERATURE OF 614°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING SOCONY 109-F OIL IN A N_2 BLANKET

(BEARING NO. 556 ON DRIVE END FROM RUN NO. 49)

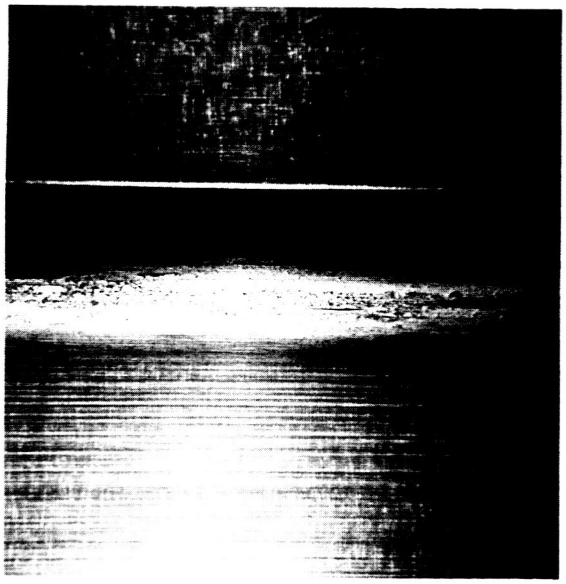


CAGE-1



CAGE

INNER RACEWAY

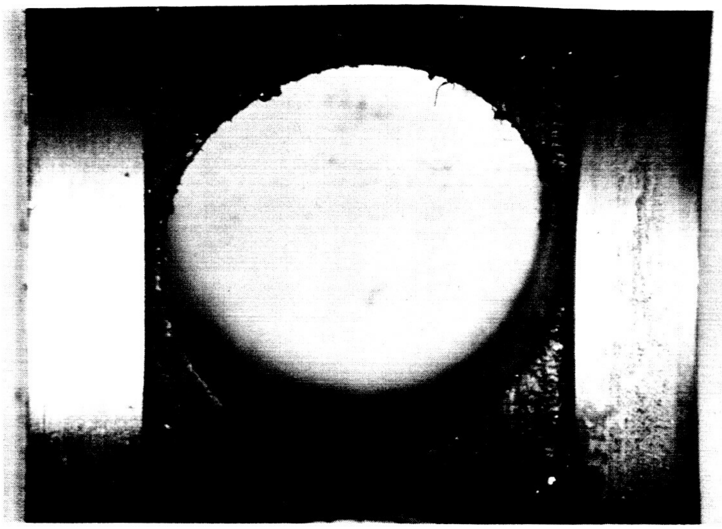


OUTER RACEWAY

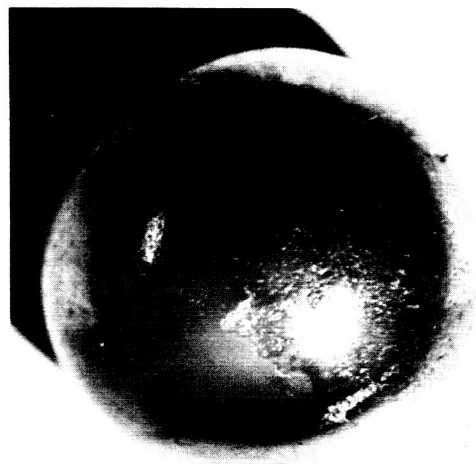
ENCLOSURE 23 **AL64T055**

FAILED WB49 TOOL STEEL BEARING AFTER RUNNING 10.9 REVOLUTIONS AT 40,000 RPM, A MEAN TEMPERATURE OF 550°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING KENDEX 0846 OIL IN A N_2 BLANKET

(BEARING NO. 561 ON DRIVE END FROM RUN NO. 50)



CAGE



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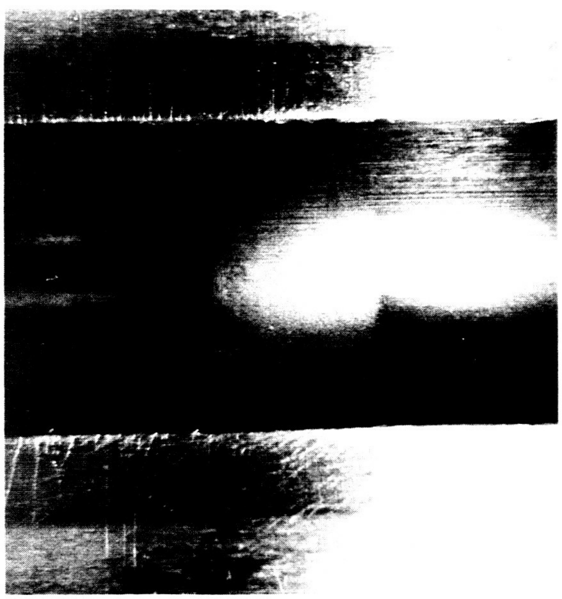
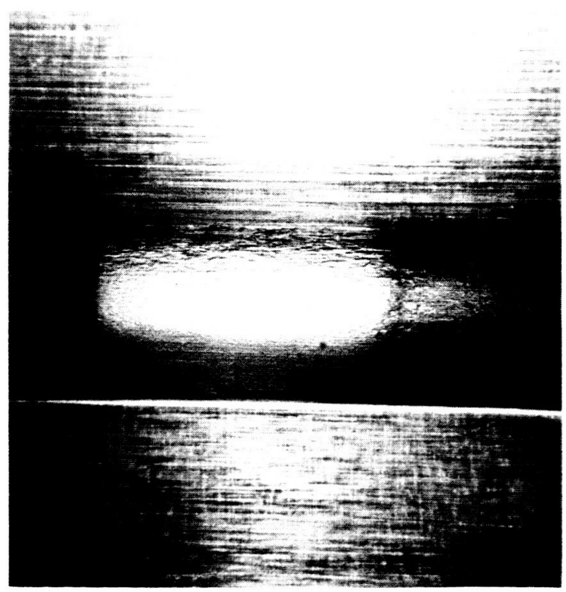


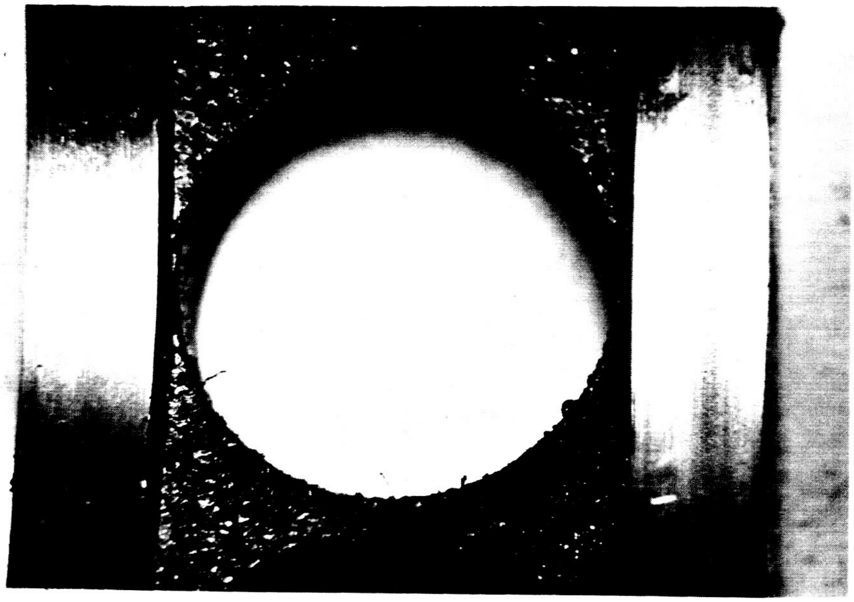
INNER RACEWAY



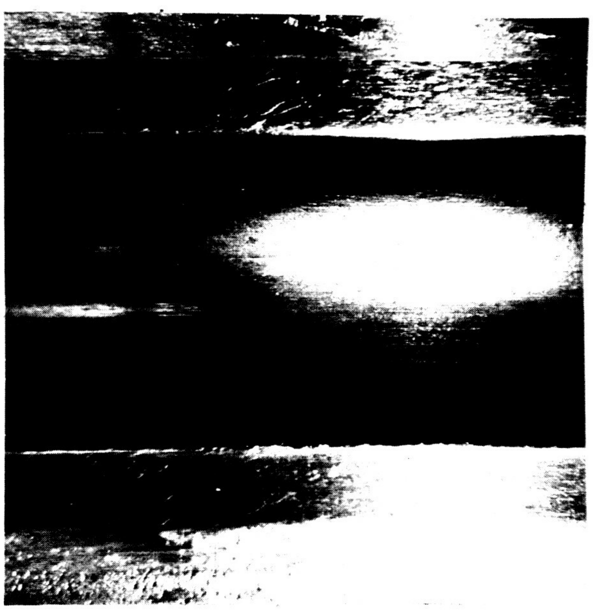
OUTER RACEWAY

UNFAILED WB49 TOOL STEEL BEARING AFTER RUNNING 10.9×10^6 REVOLUTIONS AT 40,000 RPM, A MEAN TEMPERATURE OF 606°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING KENDEX 0846 OIL IN A N_2 BLANKET

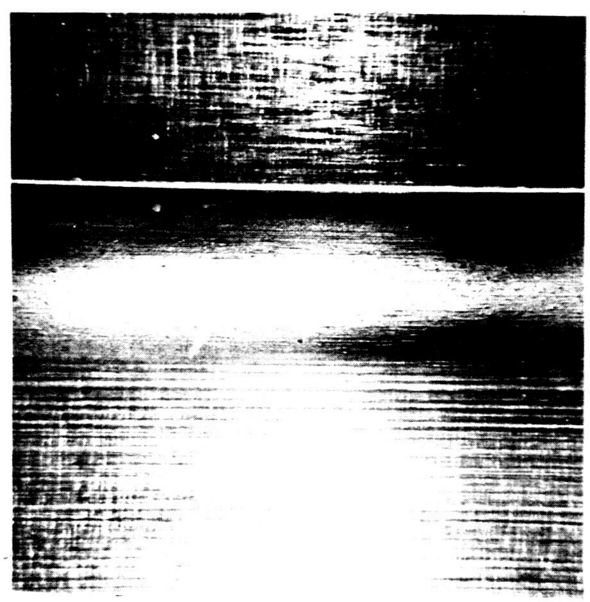
(BEARING NO. 558 ON LOAD END FROM RUN NO. 50)



CAGE



INNER RACEWAY

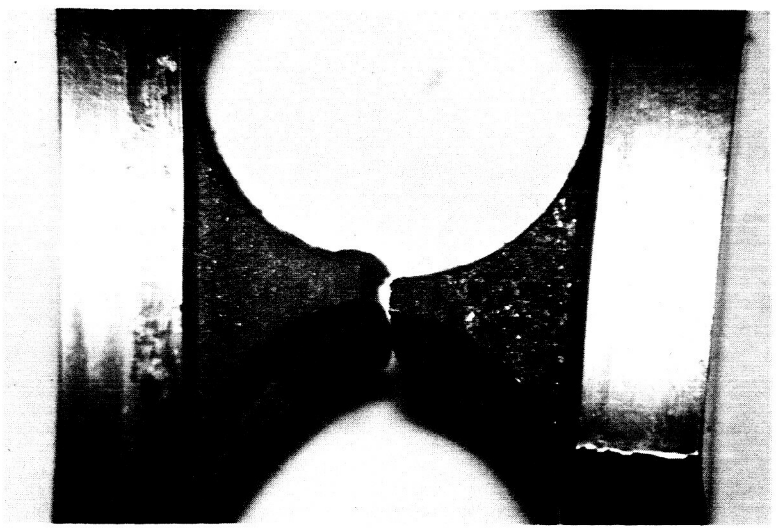


OUTER RACEWAY

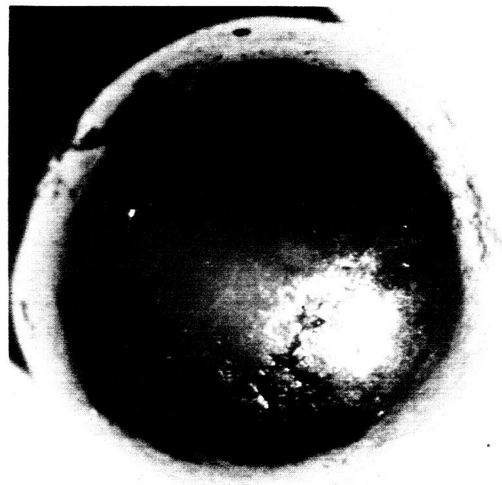
ENCLOSURE 25 **AL64T055**

FAILED WB49 TOOL STEEL BEARING AFTER RUNNING 40.8×10^6 REVOLUTIONS AT 40,000 RPM, A MEAN TEMPERATURE OF 565°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING ESSO TURBO 35 OIL IN A N_2 BLANKET

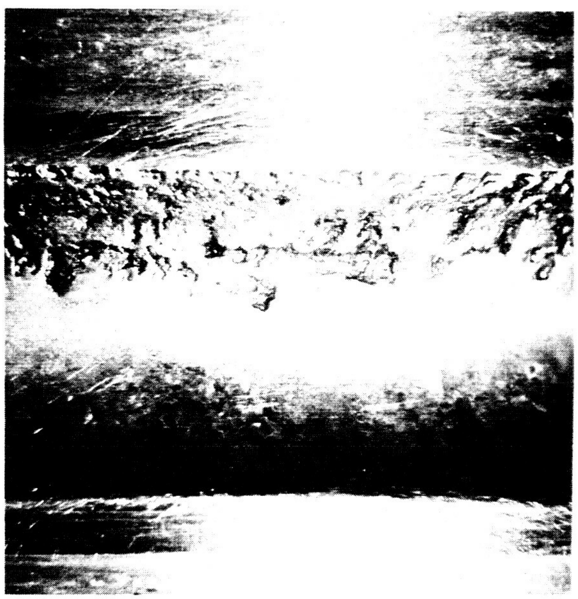
(BEARING NO. 553 ON LOAD END FROM RUN NO. 51)



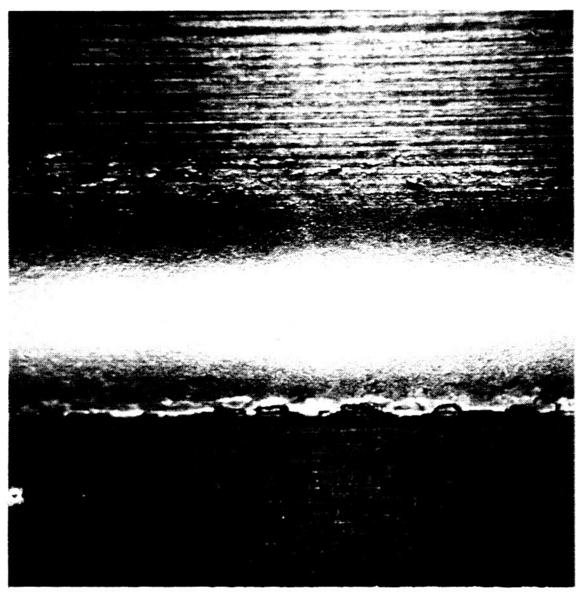
CAGE



BALL



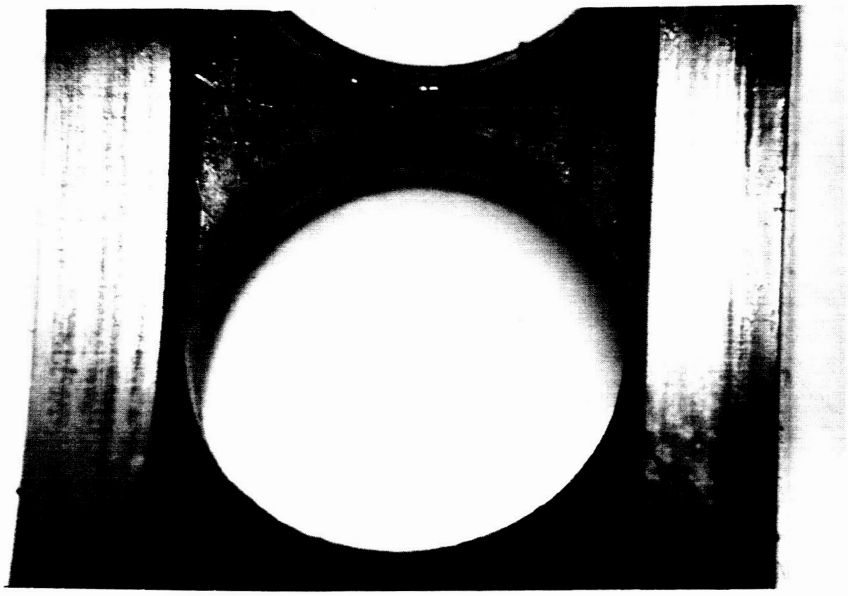
INNER RACEWAY



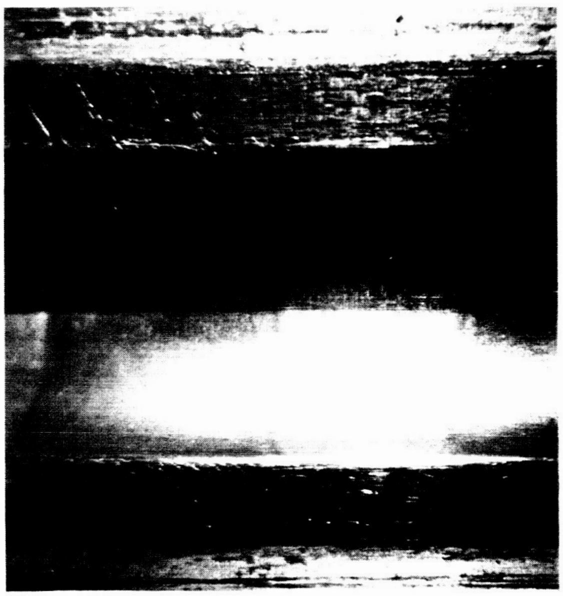
OUTER RACEWAY

UNFAILED WB49 TOOL STEEL BEARING AFTER RUNNING 40.8 x 10^6 REVOLUTIONS AT 40,000 RPM, A MEAN TEMPERATURE OF 465°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING ESSO TURBO 35 OIL IN A N_2 BLANKET

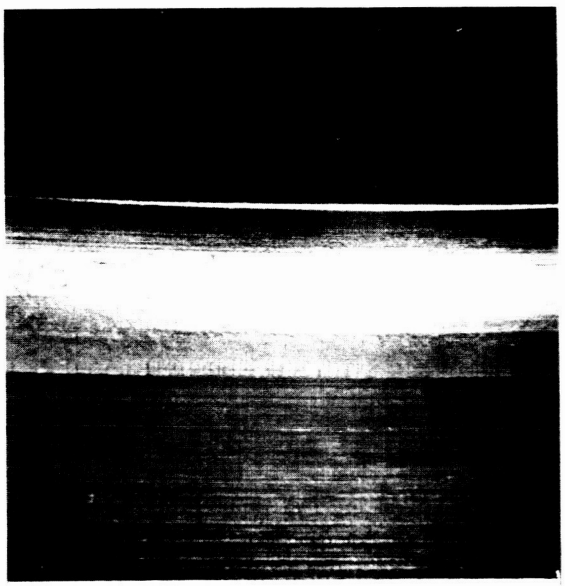
(BEARING NO. 554 ON DRIVE END FROM RUN NO. 51)



CAGE



INNER RACEWAY



OUTER RACEWAY

CAGE COMPATABILITY TEST RESULTS WITH HIGH TEMPERATURE LUBRICANTS AT 1200 RPM AND 1000 LBS. LOAD

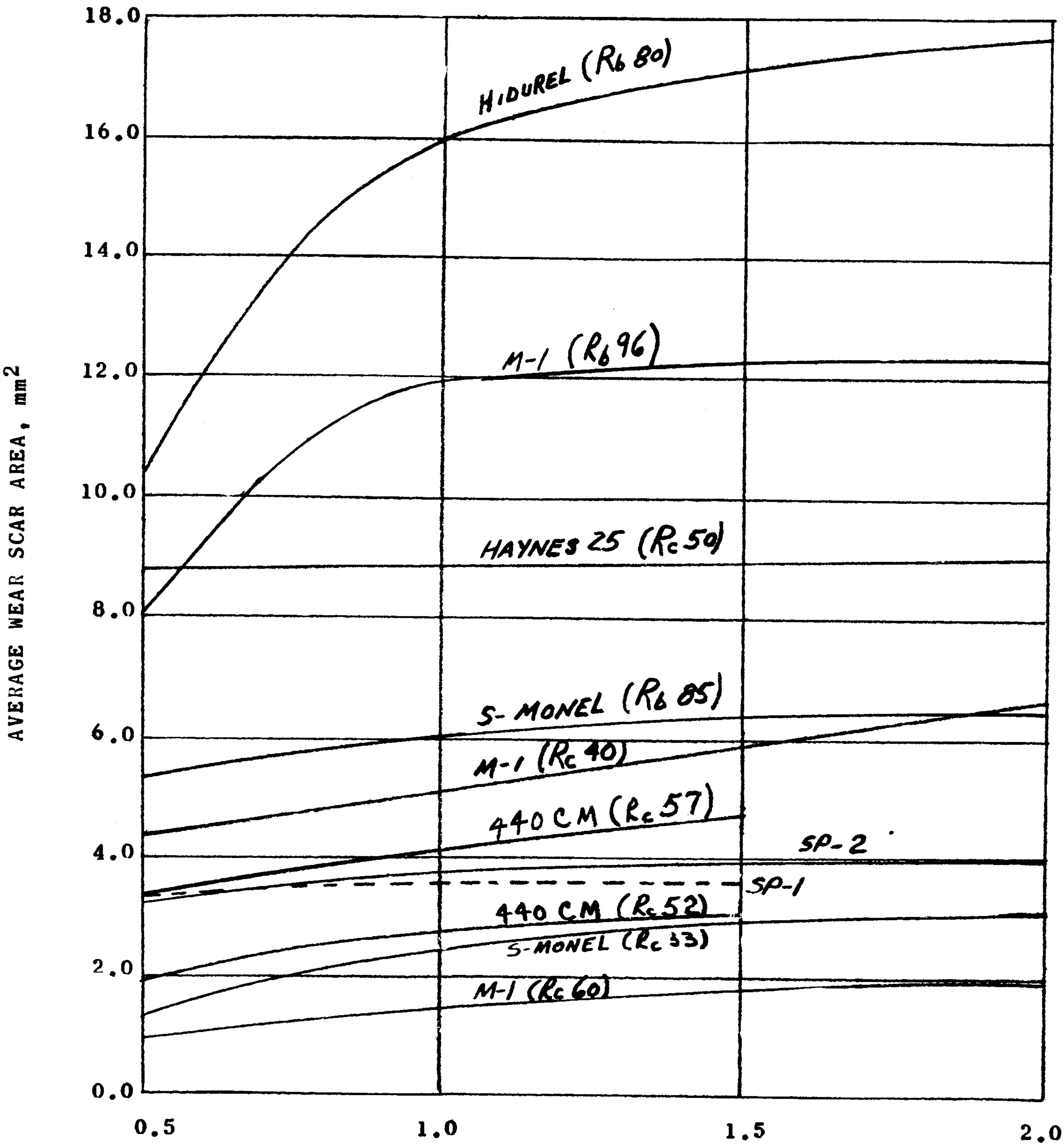
Test No.	Cage Mat'l	Hardness	Lubricant	Lubr. Flow cc/Min.	Temp. °F	Hrs. Run	Average Wear Scar: Major Axis (MM)	Average Wear Scar: Minor Axis (MM)	Average Wear Scar: Area (MM^2)	N_2 Flow Setting S.C.F.H.	Oil After Test: Visc. at 100°F CS	Oil After Test: Acid No.	Oil After Test: Solids MG/100 ML
62	440CM	Rc57	FN-3157	5.0	500	0.5	4.1	1.0	3.4	2.0	81.0	.06	7.0
						1.5	4.9	1.2	4.7				
63	440CM	Rc57	OS-124	2.0	700	0.5	4.1	1.1	3.5	4.0	374.5	.06	110.0
						1.5	4.5	1.1	3.9				
64	440CM	Rc52	OS-124	2.0	700	0.5	4.3	1.3	4.4	2.0	-	.06	35.0
						1.5	4.7	1.4	5.2				
66	M-1	Rc60	MLo 64-9	2.5	700	0.5	2.1	0.8	1.4	2.0	400.1	.06	12.0
						1.5	2.8	1.0	2.1				
67	S-Monel	Rc33	MLo 64-9	3.5	700	0.5	4.8	1.8	6.8	2.0	397.2	.06	17.0
						1.5	6.2	2.4	11.6				
68	440CM	Rc52	FN-3157	4.0	500	0.5	3.3	0.7	1.8	2.0	84.1	.06	36.4
						1.5	3.6	1.0	2.9				

THE UNUSED OILS HAVE THE FOLLOWING PROPERTIES:

Lubricant	Visc. at 100°F, CS	Acid No.	Solids, MG/100 ML
FN-3157	80.4	0.11	2.0
OS-124	348.6	0.11	21.0
MLo 64-9	305.0	-	-

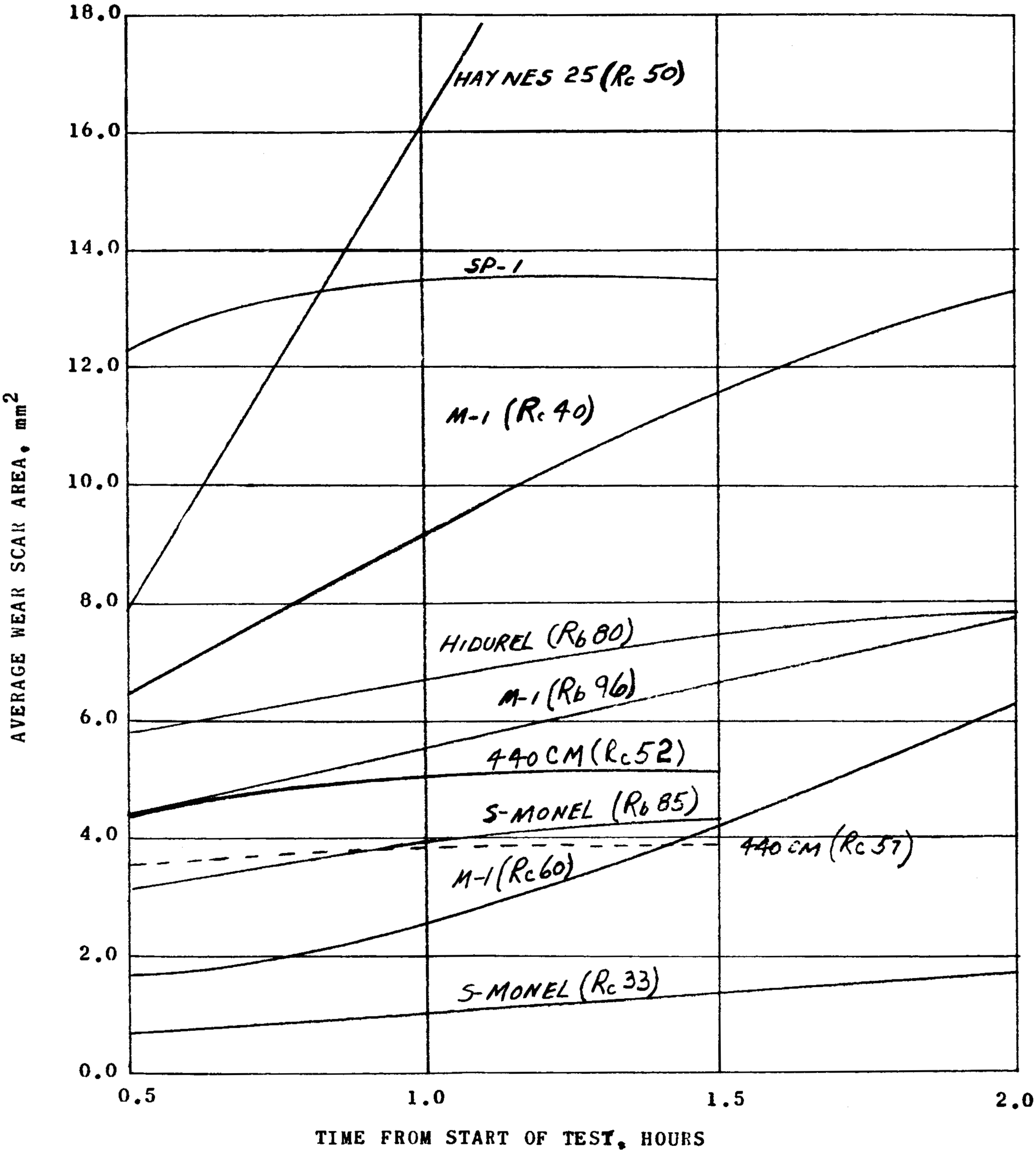
CAGE COMPATABILITY TEST RESULTS WITH ESSO FN-3157 OIL
AT 500°F, 1,000 LBS. LOAD AND 1,200 RPM

(AVERAGE WEAR SCAR AREA VS. HOUR RUN)



CAGE COMPATABILITY TEST RESULTS WITH MONSANTO OS-124 OIL AT 700°F, 1,000 LBS. LOAD AND 1,200 RPM

(AVERAGE WEAR SCAR AREA VS. HOURS RUN)



CAGE COMPATABILITY TEST RESULTS WITH M10-64-9 OIL AT 700°F, 1,000 LBS. LOAD AND 1,200 RPM.

(AVERAGE WEAR SCAR AREA VS. HOURS RUN)